



# **Downscaling Temperatures to Shenandoah National Park using Gridded Climate Data Sets, High-Resolution Atmospheric Models, and Surface Observations**

*Final Report in Completion of Cooperative Agreement  
484010004*

Natural Resource Technical Report NPS/SHEN/NRTR—2014/875



**ON THE COVER**

View from Hawksbill Mountain

Photograph by: courtesy of Shenandoah National Park

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## Executive Summary

From 1 June 2010 to 31 May 2013, a collaborative project “Adaptive management, climate change, and endangered species: a case study of Shenandoah salamanders” was conducted between the National Park Service (NPS), the United States Geological Survey (USGS), and the University of Virginia (UVA). The objectives of the UVA portion of the project were to relate the variability in temperature and humidity in the habitat of the Shenandoah Salamander (*Plethodon shenandoah*) to long-term climatological measurements in Shenandoah National Park (SNP) and to assess changes in these variables under different climate change scenarios. To fulfill these objectives, we used output from regional climate models (RCMs), output from the Weather Research and Forecasting (WRF) model which is a state-of-the-art mesoscale atmospheric model, long-term climate observations from two mountaintop stations within SNP, high-resolution gridded climate data sets, and data collected from a network of 60 temperature-humidity sensors that we deployed in SNP during this project.

To generate maps of present-day spatial temperature variability within SNP, we developed a statistical downscaling technique of high-resolution gridded climate data sets, and we performed dynamical downscaling using WRF simulations. We evaluated gridded climate data sets, focusing on the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (4 km<sup>2</sup> spatial resolution over the coterminous US), but also showing some results from DAYMET (1 km<sup>2</sup> spatial resolution), using observations from the two long-term climate monitoring sites within SNP (Big Meadows: 38.53 N, -78.44 W, 1079 m above mean sea level [msl]; and Pinnacles: 38.62 N, -78.35 W, 1017 m msl) and data from our network of temperature-humidity sensors. We found a warm bias of the maximum temperatures in PRISM and DAYMET that was a function of the slope orientation, season, and elevation. This bias was largest in the summer on east-facing slopes and smallest in the winter on west-facing slopes. We focus on July because *P. shenandoah* is expected to exhibit a greater response to changes in summer extremes in maximum temperature than to changes in minimum temperature. In the case of mean July maximum temperatures, there was a warm bias in PRISM of 2°C (4°C) along the west (east) side of the Blue Ridge at the sites where we measured temperature. The bias in DAYMET was larger than PRISM. In DAYMET, the mean difference between the observations and downscaled results along the west and east slopes of the Blue Ridge for July was 4°C and 6°C, respectively. For both PRISM and DAYMET, we included a correction in our downscaling approach using an empirical offset so that we could produce more accurate high-resolution maps of mean July maximum temperature for the present day. Output from the dynamical downscaling approach using WRF showed better agreement with the observations than results from the statistical approach using PRISM and DAYMET, with mean differences between the model and observations <1.5°C for mean monthly maximum temperature in July.

Our statistical downscaling approach is appropriate for maximum temperature but not for atmospheric moisture variables, including relative humidity and precipitation. Humidity for example is affected by multiple near-surface processes and can exhibit large spatial variations that can occur independently of elevation. Furthermore, high-resolution gridded data sets of atmospheric moisture are not available in PRISM at the same high resolution as temperature.

We used our statistical downscaling approach for temperature to create high-resolution (15 m) maps of future climate change projections of mean July maximum temperature within SNP under a variety of emissions scenarios obtained from the North American Regional Climate Change Assessment Program (NARCCAP). Within the suite of 7 NARCCAP RCMs that we used, maximum temperatures are expected to increase within SNP at a rate of  $0.47^{\circ}\text{C decade}^{-1}$  (i.e.  $3.3^{\circ}\text{C}$  over a 70-year period between 1985 and 2055). Mean July minimum temperatures are expected to increase  $0.41^{\circ}\text{C decade}^{-1}$ , which represents about a  $2.9^{\circ}\text{C}$  increase between 1985 and 2055. Because NARCCAP uses only one emissions scenario (A1B, which assumes moderate fossil fuel emissions), we evaluated output from other RCMs that use different fossil fuel emissions scenarios. We used output from the International Center for Theoretical Physics RCM Version 3 and found that, under the most extreme climate change scenarios (SRES A1F1), maximum temperatures within SNP may increase at a rate of  $\sim 0.7^{\circ}\text{C decade}$ .

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We thank the following people from the University of Virginia Department of Environmental Sciences for assisting with the field work in this project. Special thanks to Dr. Zeljko Vecenaj, M.S. candidate Stephanie Phelps, as well as to the following undergraduates: Nathan Brown, Sydney Delmar, Douglas Lawrence, Angang Li, Christopher Muir, Amelia Nystrom, and Elizabeth Stoner. NARCCAP data obtained from <https://www.narccap.ucar.edu/>. PRISM and DAYMET data are available from <http://prism.oregonstate.edu/> and <http://DAYMET.ornl.gov/datasupport>, respectively.

## List of Terms

|           |                                                                          |
|-----------|--------------------------------------------------------------------------|
| AGL       | Above Ground Level                                                       |
| CADCO     | Central Appalachian Dry chestnut oak                                     |
| CADCROF   | Central Appalachian dry-mesic chestnut oak-northern red oak forest       |
| CAMOHF    | Central Appalachian montane oak-hickory forest                           |
| CANHF     | Central Appalachian northern hardwood forest                             |
| CASTNET   | Clean Air Status and Trends Network                                      |
| CCSM-CRCM | Community Climate System Model-Canadian Regional Climate Model           |
| CCSM-WRFG | Community Climate System Model-Weather Research and Forecasting Model    |
| CGCM-CRCM | Coupled General Circulation Model-Canadian Regional Climate Model        |
| CGCM-RCM3 | Coupled General Circulation Model-Regional Climate Model Version 3       |
| CGCM-WRFG | Coupled General Circulation Model-Weather Research and Forecasting Model |
| DAYMET    | Daily Surface Weather and Climatological Summary                         |
| DEM       | Digital Elevation Model                                                  |
| GCM       | General Circulation Model                                                |
| GFDL-HRM3 | Geophysical Fluid Dynamics Model-Hadley Regional Model Version 3         |
| GFDL-HRM3 | Geophysical Fluid Dynamics Model-Hadley Regional Model Version 3         |
| GPS       | Global Positioning System                                                |

|                      |                                                             |
|----------------------|-------------------------------------------------------------|
| HOBO                 | Honest Observer by Onset                                    |
| ICTP                 | International Center for Theoretical Physics                |
| LSM                  | Land Surface Model                                          |
| MBE                  | Mean Bias Error                                             |
| MSL                  | Mean Sea Level                                              |
| NARCCAP              | North American Regional Climate Change Assessment Program   |
| NCAR                 | National Center for Atmospheric Research                    |
| NCDC                 | National Climate Data Center                                |
| NOAA                 | National Oceanic and Space Administration                   |
| NPS                  | National Park Service                                       |
| NROF                 | Northern red oak forest                                     |
| <i>P. shenandoah</i> | <i>Plethodon shenandoah</i>                                 |
| PRISM                | Parameter-elevation Regressions on Independent Slopes Model |
| RCM                  | Regional Climate Model                                      |
| RMSE                 | Root Mean Square Error                                      |
| SNP                  | Shenandoah National Park                                    |
| SRES                 | Special Report on Emission Scenarios                        |
| USGS                 | United States Geological Survey                             |
| UTM                  | Universal Transverse Mercator                               |
| UVA                  | University of Virginia                                      |
| WRF                  | Weather Research and Forecasting                            |
| WMO                  | World Meteorological Organization                           |

## Introduction

Studying the potential impacts of climate change is vital to improving the management of natural resources in national parks. The most significant impacts are expected at high elevations where many national parks are located (e.g. Saunders et al., 2009). Many species within these national parks are highly sensitive to changes in temperature and moisture and thus have a limited habitat. One example is the Shenandoah salamander, *Plethodon shenandoah* (*P. shenandoah*). This salamander is found nowhere else in the world aside from 6 square kilometers above 900 m in the Shenandoah National Park (SNP). Future climate projections suggest changing temperature and moisture patterns in many regions including SNP, but it is unclear how these changes will impact the local climate and the limited habitat of *P. shenandoah*. It is important to understand the impacts of climate change on the local climate in these habitats, as this can help the park administrators manage the area's natural resources and to take the necessary steps to preserve these endangered species.

To help understand climate change projections within SNP, the goals of the University of Virginia (UVA) portion of this project were to:

1. Relate the variability in temperature and humidity in the habitat of *P. shenandoah* to long-term climatological measurements in Shenandoah National Park (SNP).
2. Assess the potential changes in temperature and relative humidity under various climate change scenarios.

To achieve these goals, we completed the tasks summarized in Table 1.

During Year I of the project (1 June 2010 – 31 May 2011), we began a preliminary evaluation of climate projections for the Mid-Atlantic region that were based on output from a selection of regional climate models (RCMs) available from the North American Regional Climate Change Assessment Program (NARCCAP, <http://www.narccap.ucar.edu/>). To facilitate statistical downscaling of NARCCAP RCM projections to SNP, we began evaluating existing high-resolution gridded climate data sets and compared these with meteorological observations collected at a long term weather station in Big Meadows, SNP. To downscale climate projections to other locations in the park, we needed to determine current temperature and humidity relationships between the weather station at Big Meadows and other regions of SNP. To do so, we deployed a network of 57 HOBO temperature/humidity loggers and began analyzing data collected from this network.

In Year II of the project, we analyzed climate data from NARCCAP RCMs, as well as RCMs that used different fossil fuel emissions scenarios. To assist in downscaling these models to SNP, we developed a method to statistically downscale existing high-resolution gridded climate data sets and evaluated the method using data obtained from the network of HOBO loggers deployed during Year I. We also began the setup and testing of the Weather Research and Forecast (WRF) model for SNP,

which was used to dynamically downscale climate model output to SNP during Year III (1 June 2012 – 31 May 2013).

During the final year of the project (Year III), we evaluated the relationship between temperature and relative humidity at Big Meadows and the habitat of *P. shenandoah* and used WRF to dynamically downscale climate model output to SNP. We then used our statistical downscaling approach from Year II and dynamically downscaled model output from Year III to produce maps of the spatial variation in temperature for both the present and for three different emissions scenarios that make different assumptions about future energy use (IPCC, 2007):

Special Report on Emission Scenarios (SRES) A1B makes the assumption that energy is generated from a balanced use of fossil fuels and non-fossil fuels (IPCC, 2007).

SRES B1, like the A1B scenario, is also a moderate climate change scenario. SRES B assumes that, with the introduction of cleaner energies in the middle 21<sup>st</sup> century, atmospheric CO<sub>2</sub> mixing ratios will stabilize around 550 ppm in Year 2100 (IPCC, 2007).

SRES A1FI, which is more pessimistic than the SRES A1B and SRES B scenarios, assumes that energy will be generated from mostly fossil fuels, causing CO<sub>2</sub> emissions to exceed 1000 ppm in Year 2100 (IPCC, 2007).

Though one of the objectives of this study was to quantify projected future changes in humidity at high resolution in SNP, we soon realized the limitations of developing reliable humidity projections. These limitations arise partly because the relationship between humidity and elevation is more complicated than the relationship between temperature and elevation. Also, relative humidity is not available at high resolution in PRISM, one of the pre-existing gridded climate data sets we used in this report. Finally, there was much more variability in the humidity projections from the NARCCAP RCMs than there was for temperature; some NARCCAP RCMs projected increases in moisture in SNP and the surrounding region, whereas other NARCCAP RCMs indicated decreasing trends in moisture. Given these uncertainties and limitations, future projections of humidity at high resolution would have been unreliable in SNP and thus we focus on temperature downscaling in this report.

**Table 1.** Summary of tasks completed. The year(s) of completion is noted in the second column. Year I indicates tasks completed 1 June 2010 – 1 June 2011; Year II indicates work done 1 June 2011 – 1 June 2012; and Year III indicates work done 1 June 2012 – 31 May 2013.

| Task                                                                                                                         | Year(s)<br>Completed |
|------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Make GIS maps of habitat                                                                                                     | I                    |
| Purchase and laboratory inter-comparison of temperature/humidity data loggers                                                | I                    |
| Deploy a network of temperature and relative humidity dataloggers across the potential range of <i>P. Shenandoah</i>         | I                    |
| Maintain network for two years with bi-monthly visits to download data/check sensors                                         | I, II, III           |
| Develop relationships between temperatures/humidity at Big Meadows and the habitat from sensors                              | III                  |
| Develop software to extract PRISM data for selected location in SNP                                                          | I                    |
| Analyze PRISM data                                                                                                           | I, II, III           |
| Analyze Big Meadows data                                                                                                     | I, II, III           |
| Develop relationships between temperatures/humidity at Big Meadows and the habitat from PRISM                                | II, III              |
| Set up a numerical meteorological model                                                                                      | II, III              |
| Run the model for variety of atmospheric conditions                                                                          | III                  |
| Evaluate model output                                                                                                        | III                  |
| Develop relationships between temperatures/humidity at Big Meadows and the habitat from high resolution atmospheric modeling | III                  |
| Write final report                                                                                                           | III                  |

In the present report, we summarize the aforementioned analyses and how they are used to produce models and maps of the current spatial variability of minimum and maximum and relative humidity within the habitat, as well as projections of these variables within the habitat of *P. shenandoah* under a variety of emission scenarios. We focus on July because *P. shenandoah* is expected to exhibit a greater response to changes in summer extremes in maximum temperature than to changes in minimum temperature. In the second section of this report, we first present an overview of our statistical and dynamical downscaling approaches and describe the observations and models in more detail. We present our results on present-day temperature variations in SNP and maps of current and projected temperature changes within SNP in the third section. In the final section, we summarize these results and present recommendations on the use of our results.



## Methods

To statistically and dynamically downscale climate data to SNP, we use a variety of both short- and long-term observations from in and around SNP, high-resolution gridded climate data sets, a high-resolution atmospheric mesoscale model, and output from regional climate models. Each of these products is discussed in more detail in this section.

### 2.1 Overview of approach to downscaling climate data

The grid spacing of general circulation models (GCMs), which is on the order of a few hundred kilometers, is far too coarse to resolve the impacts of climate change at regional- to local scales. For this reason, regional climate models (RCMs) are one method used to downscale output from GCMs. Nevertheless, RCM spatial resolution of a few tens of kilometers is still far too coarse to assess climate change on the scale of local habitats. In the example in Figure 1, a 50 km grid spacing associated with an RCM averages the elevation changes across the grid. Because the elevations are averaged over a 50 km resolution, the topographical features within Shenandoah National Park (SNP) are completely removed, which makes it very difficult to understand projected climate changes at high-elevation habitats within this region. Furthermore, climate models with this resolution do not resolve unique atmospheric processes in mountainous areas such as drainage flows and cold air pooling. To be most representative in SNP, downscaling climate model output to the local scale must include the effects of these terrain-induced atmospheric processes.

To downscale future climate projections to SNP, we employ both a statistical approach and a dynamical approach. In our statistical approach, we use the Parameter-elevation Regressions on Independent Slopes Model (PRISM) model, which is a high-resolution gridded climate data set and has an 800 m spatial resolution over the contiguous US (e.g. Daly et al., 2001), as well as DAYMET which is another widely-used high-resolution gridded climate data set (Thornton et al., 1997). In addition to using PRISM and DAYMET, we run the Weather Research and Forecasting (WRF) model, which is a state-of-the-art mesoscale meteorological model (Skamarock et al., 2008), for a domain that encompasses all of SNP. Both PRISM and WRF are used to generate high-resolution near-surface temperature fields at the spatial scale of <1 km. We then evaluate both of these models using data from a network of temperature sensors deployed in SNP in 2011. Based on the relationships between the models (PRISM and WRF) and the observed temperatures, we develop corrections to the modeled temperature and use these corrections to produce high-resolution (15 m) maps of current (July, 2012 as an example) temperature within SNP. We then apply our knowledge gained about present-day near-surface temperature variations to statistically downscale future climate output from RCMs to SNP. This downscaling procedure is summarized in Figure 1.

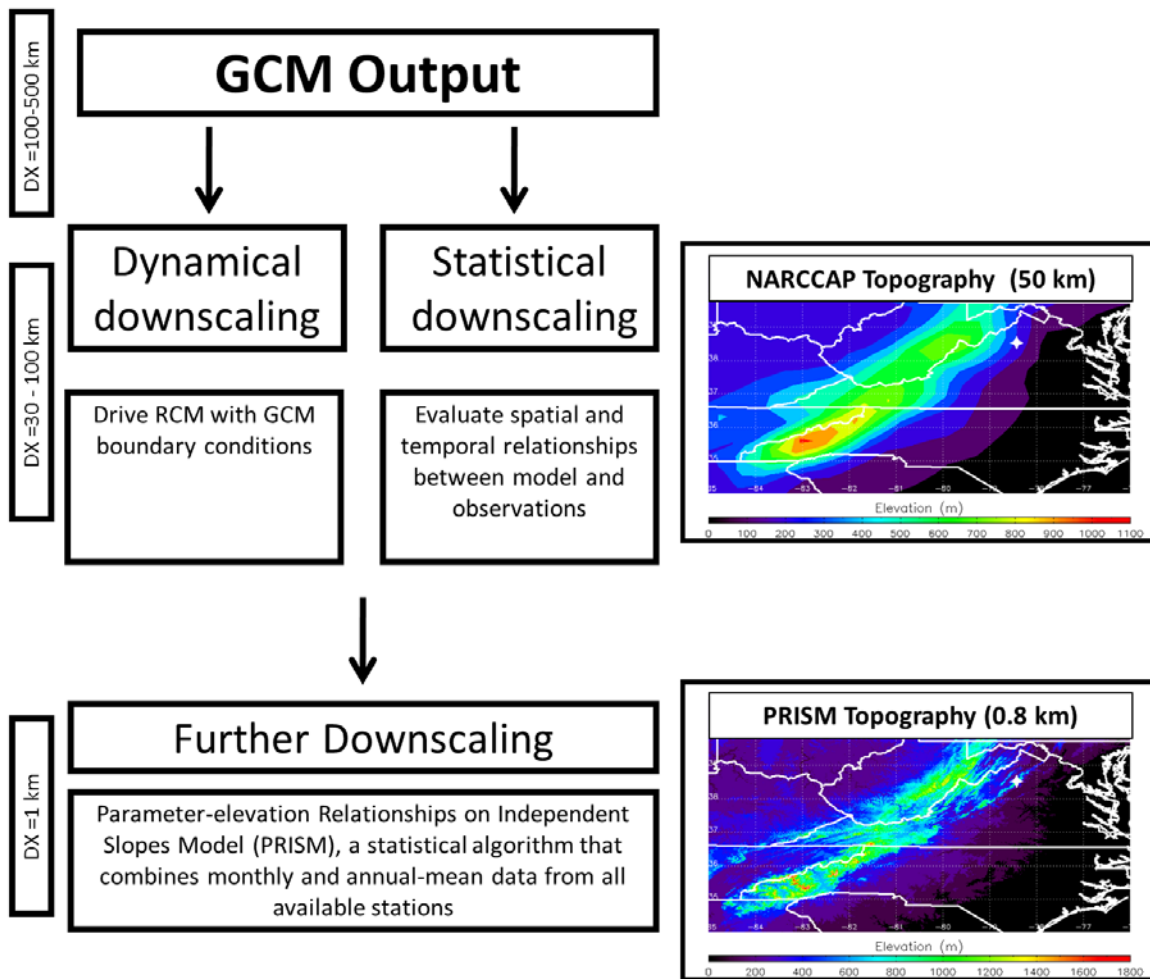


**Figure 1.** Summary of downscaling approach. Output from GCMs (which have spatial scales typically of about 100-500 km) can be downscaled to finer spatial resolutions (~30 to 100 km) using either a dynamical approach or statistical approach. Spatial scales of this magnitude are still too coarse to resolve many relatively small mountain ranges, e.g. the Blue Ridge Mountains, as shown in the upper map (white star denotes location of Big Meadows) in the topography data set that is used for all NARCCAP RCMs. Thus, further downscaling is required using atmospheric mesoscale models (e.g. WRF) that we run at high (1 km) resolution and/or high-resolution gridded climate data sets (e.g. PRISM), which can better resolve the regional topography, as shown in the lower map.

## 2.2. Site Conditions

The habitats of *P. shenandoah* are located along the mountain ridges of the central portion of Shenandoah National Park (SNP) (Figure 2). SNP itself is located along the crest of the Virginia Blue Ridge Mountains in the eastern US and is oriented southwest-northeast. It extends 115 km from near Waynesboro, Virginia to Front Royal, Virginia with elevations ranging from 200 m above mean sea level (msl) in the valleys to 1000-1200 m msl along the ridgeline. The habitats of *P. shenandoah* encompass only a small area of SNP and extend from north of Big Meadows (a site with a long term climate monitoring station that will be discussed further in the next section) to south of the Thornton Gap entrance station. The habitats extend from the ridgeline to 800 m msl along the eastern slope and to 700 m msl along the western slope.

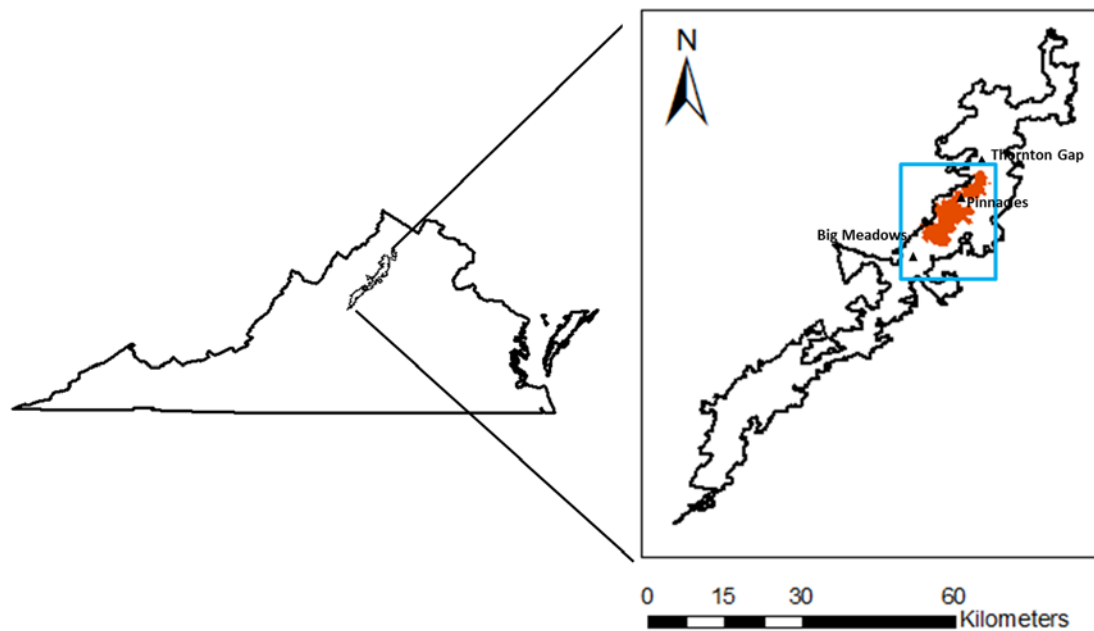


**Figure 2.** Location of SNP within Virginia (left panel). Right panel shows relative location of the habitats of *P. shenandoah* (orange shading) within SNP. The locations of Thornton Gap, Pinnacles, and Big Meadows, the latter two of which are long-term mountaintop climate monitoring stations in SNP, are indicated by a black triangle and are labeled. The blue box encompasses the region shown in Figure 3.

## **2.3. Meteorological measurements**

Meteorological measurements are made at several locations in SNP. Long-term measurements are made at Big Meadows, which features a nearly-continuous 78-year observation record (as of July, 2013), as well as at Pinnacles, where meteorological observations have been made since 2008. In addition, measurements of temperature and relative humidity are available at many locations along the west and east sides of SNP beginning in 2011. Next, we describe the various meteorological measurements at SNP in more detail.

### **2.3.1. Long-term measurements**

Daily observations of temperature and precipitation have been made at Big Meadows weather station (38.53 N, -78.44 W, 1079 m msl) since 1935 and are available from the National Climate Data Center (NCDC). Data from the long-term climate data set are used to determine long-term climate trends at the site.

In addition, hourly observations at Big Meadows of a suite of meteorological variables began in 1989 as part of the Environmental Protection Agency (EPA) Clean Air Status and Trends (CASTNET) network and include observations of temperature measured 2 m and 10 m above ground level (agl), wind speed and direction 10 m agl, incoming shortwave radiation, barometric pressure, and precipitation. In January, 2011, the 2 m temperature sensor was removed from the site because of lack of funding for repair (Elizabeth Garcia, personal communication). For this reason, we installed a HOBO Pro V2 temperature-relative humidity logger at the site and use these data when evaluating our downscaling approach on most recent climate data.

We also use meteorological data from Pinnacles weather station, located about 14 km northeast of Big Meadows (38.62 N, -78.35 W, 1017 m msl). Beginning in July 2008, the University of Virginia (UVA) collaborators began making measurements of a suite of meteorological data at the site (Lee et al., 2012). These include measurements of temperature and wind at multiple heights, incoming and outgoing short- and long-wave radiation, barometric pressure, rainfall, and fluxes of sensible heat, latent heat, and CO<sub>2</sub>. For most of these measurements, half-hour averages (which is a common averaging frequency when making meteorological measurements) are stored onto an on-site data logger. In addition, CO and CO<sub>2</sub> mixing ratio measurements in collaboration with the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory were established in August, 2008. Meteorological data from Pinnacles are used to help further evaluate our downscaling methodologies.

### 2.3.2. Slope measurements

In April, 2011, we deployed 57 HOBO Pro V2 temperature-relative humidity loggers (Figure 3) to investigate 1) temperature lapse rates in SNP, 2) the influence of aspect and vegetation on the temperature measurements, and 3) to evaluate our downscaling approach. Lapse rate information came from the three transects descending the ridgeline: Crusher Ridge Trail (Transect 1), Skyland Fire Road (Transect 2), and Cedar Run Trail (Transect 3). Investigating the influence of aspect and vegetation on temperature came from sensors deployed in the Hawksbill Mountain cluster (Cluster 1). Sensors were installed on a fence post and positioned 2 m agl (Figure 4). We deployed HOBOS in 3 transects (Table 2): two transects along the west-facing slope of SNP and 1 transect along the east-facing slope. We had two transects along the west-facing slope of SNP so that one transect would be nearest the eastern transect and another would be near Pinnacles so we could assess spatial differences in lapse rate along the western slope.

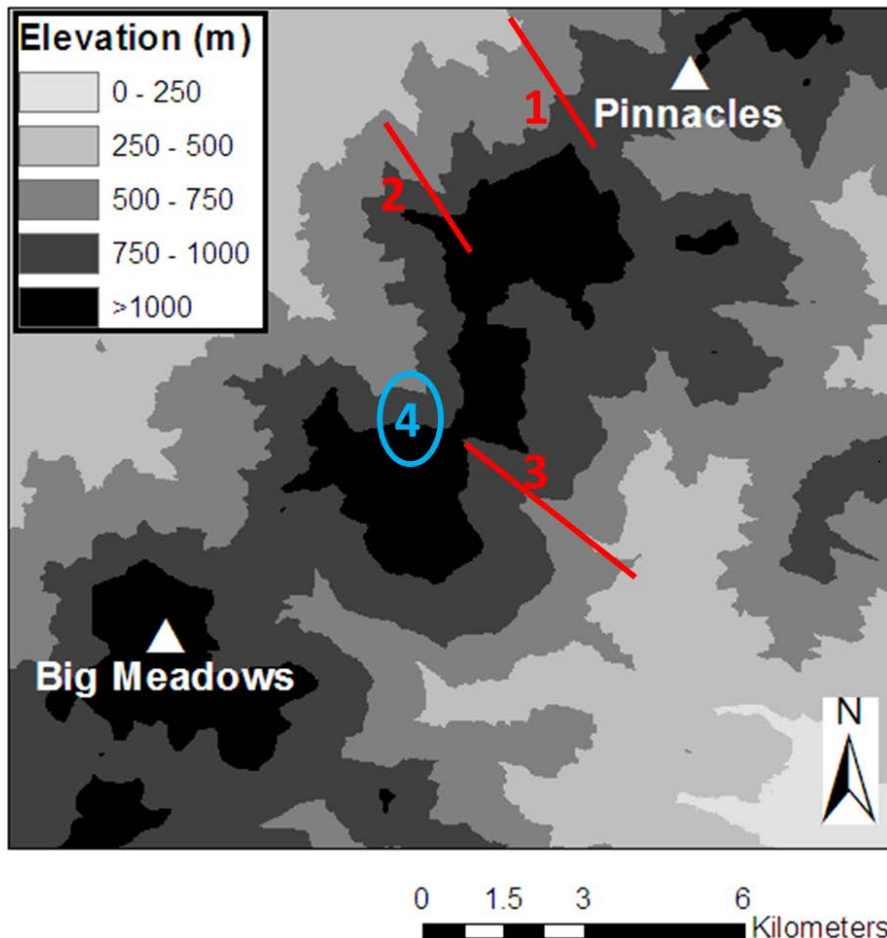


**Figure 3.** Locations of Pinnacles and Big Meadows relative to the deployment locations of the HOBO data loggers. Lines 1, 2, and 3 represent transects along the Crusher Ridge Trail, Skyland Fire Road, and Cedar Run Trail, respectively. The blue circle encompasses HOBO data loggers deployed on Hawksbill Mtn, Cluster 1.



**Figure 4.** Example of a HOBOTemperature-humidity data logger, attached to a 2 m fence post and enclosed in a radiation shield, deployed along Cedar Run Trail in SNP.

**Table 2.** Transects identified in Figure 4.

| Transect Name | Trail Name          | Number of sensors |
|---------------|---------------------|-------------------|
| Transect 1    | Crusher Ridge Trail | 5                 |
| Transect 2    | Skyland Fire Road   | 14                |
| Transect 3    | Cedar Run Trail     | 18                |
| Cluster 1     | Hawksbill           | 20                |

The transect along the east-facing slope of SNP included 18 HOBOTs (Figure 5). These were deployed in pairs at nine different elevations to assess the impact of different slope azimuths (Table 3) on the temperature measurements. The Cedar Run Trail, located along the eastern side of SNP, provided an ideal venue along which to do this experiment, as the trail is oriented approximately northwest-southeast and is much straighter than the trails along the western side of SNP. Beginning at 1000 m msl, one HOBOT was deployed along the southeast-facing slope adjacent to the Cedar Run Trail and another HOBOT was deployed along the northeast facing slope adjacent to the trail. HOBOTs were deployed approximately 50 m apart at each location, with each HOBOT approximately 25 m from the drainage; this was continued every 50 m vertically to 600 m msl for a total of 18 HOBOTs (9 pairs) deployed along Cedar Run Trail.

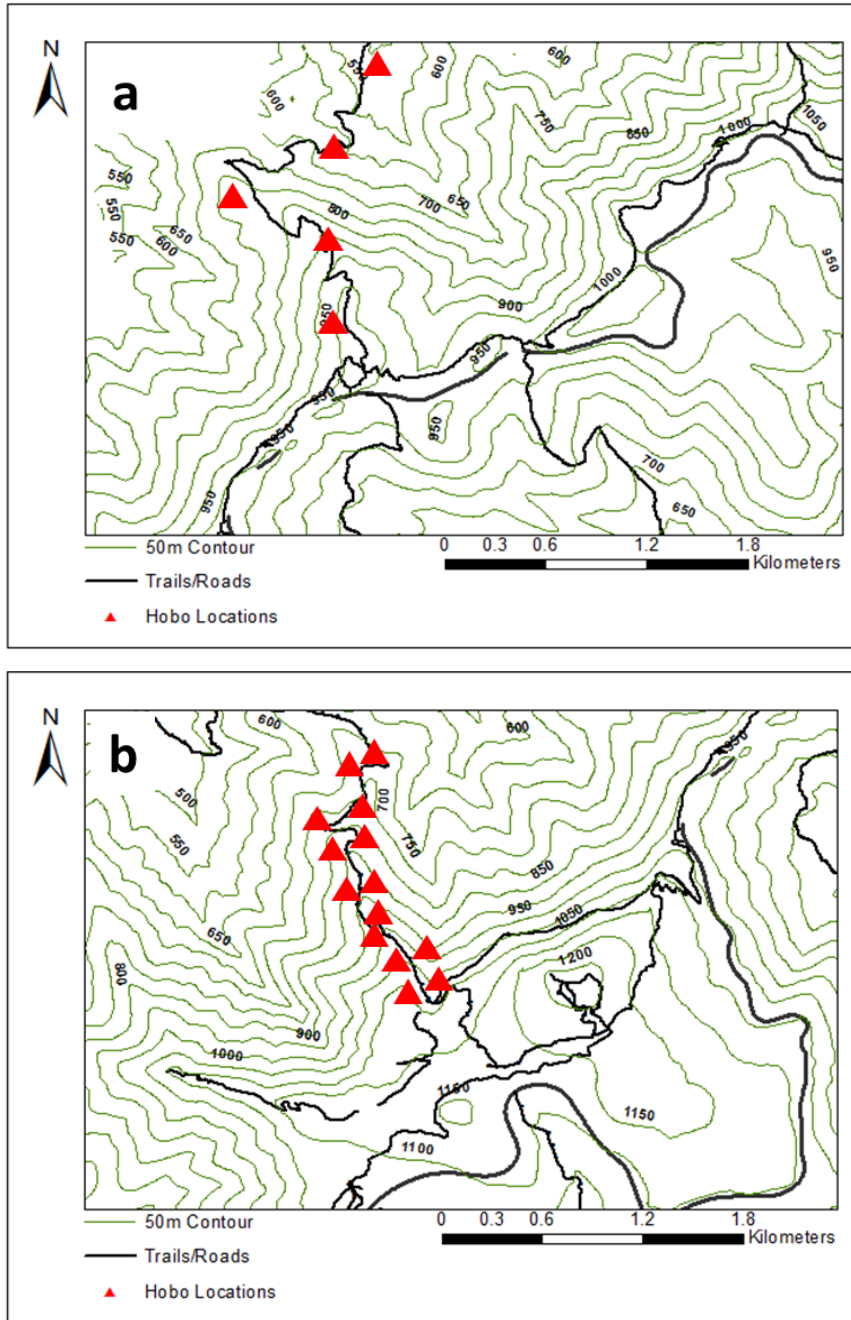


**Figure 5.** Individual HOB0 deployment locations (red triangle) along Crusher Ridge Trail (a) and Skyland Fire Road (b). Note that (a) and (b) refer to Transects 1 and 2, respectively (c. f. Figure 3, Table 2, Table 3a, Table 3b).

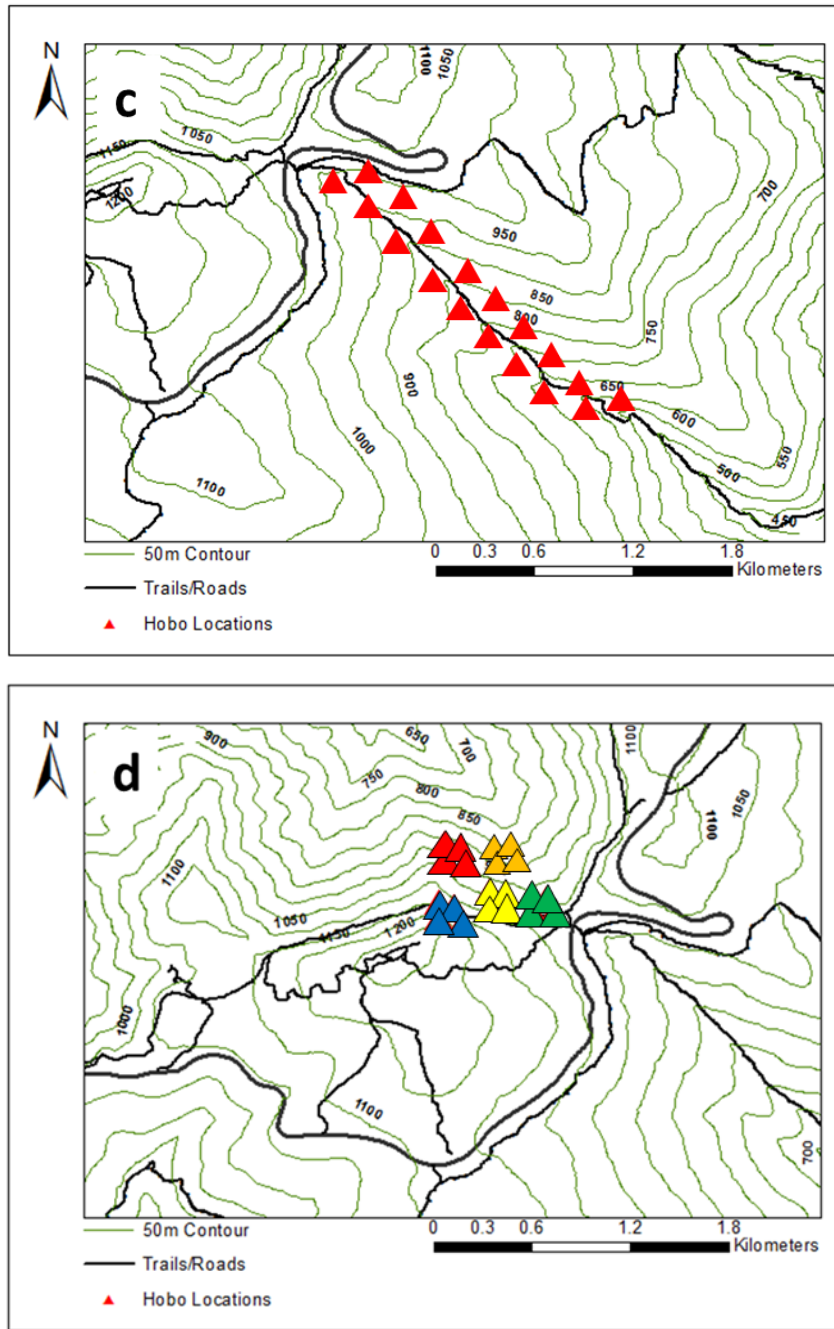


**Figure 5 continued.** Individual HOB0 deployment locations (red triangle) along Cedar Run Trail (c). Panel (d) shows the HOB0 deployment locations at Hawksbill Mountain. The green, yellow, blue, red, and orange triangles indicate HOB0 loggers deployed in the dominant vegetation types of the habitat of *P. shenandoah*: Central Appalachian dry-mesic chestnut oak-northern red oak forest (red triangles), Central Appalachian northern hardwood forest (blue triangles), northern red oak forest (yellow triangles), Central Appalachian montane oak-hickory forest (green triangles), and Central Appalachian Dry chestnut oak (orange triangles). Note that (c) and (d) refer to Transect 3 and Cluster 1, respectively (c. f. Figure 3, Table 2, Table 3a, Table 3b).

**Table 3a.** HOBO deployment locations, Transects 1-3, as well as the installation date, on-site elevation, azimuth, slope steepness, and canopy cover. Position and elevation are obtained using in-situ measurements with a handheld GPS (Global Positioning System); azimuth, slope steepness, and canopy cover are obtained for each HOBO using 15 m spatial resolution USGS ArcGIS data bases available from the USGS Leetown Science Center. Shading is used to demarcate the different transects.

| Location   | Coordinates<br>(latitude,<br>longitude) | HOBO<br>Identification<br>Number | Installation<br>Date | Elevation<br>(m msl) | Azimuth<br>(°) | Slope<br>Steepness<br>(°) | Canopy<br>Cover<br>(%) |
|------------|-----------------------------------------|----------------------------------|----------------------|----------------------|----------------|---------------------------|------------------------|
| Transect 1 | 38.62679, -<br>78.36028                 | 9810665                          | 10 Apr 2011          | 620                  | 103            | 25                        | 82                     |
| Transect 1 | 38.62634, -<br>78.36289                 | 9810627                          | 10 Apr 2011          | 692                  | 47             | 15                        | 89                     |
| Transect 1 | 38.62328, -<br>78.36477                 | 9810662                          | 10 Apr 2011          | 783                  | 264            | 9                         | 86                     |
| Transect 1 | 38.62128, -<br>78.36075                 | 9810656                          | 10 Apr 2011          | 895                  | 322            | 15                        | 94                     |
| Transect 1 | 38.61656, -<br>78.35964                 | 9810649                          | 10 Apr 2011          | 980                  | 53             | 22                        | 83                     |
| Transect 2 | 38.61006, -<br>78.38289                 | 9810658                          | 17 Apr 2011          | 730                  | 31             | 11                        | 88                     |
| Transect 2 | 38.60907, -<br>78.38390                 | 9810636                          | 17 Apr 2011          | 746                  | 281            | 27                        | 93                     |
| Transect 2 | 38.60674, -<br>78.38579                 | 9810625                          | 17 Apr 2011          | 788                  | 313            | 19                        | 93                     |
| Transect 2 | 38.60639, -<br>78.38585                 | 9810643                          | 17 Apr 2011          | 792                  | 284            | 18                        | 94                     |
| Transect 2 | 38.60517, -<br>78.38466                 | 9810637                          | 17 Apr 2011          | 853                  | 23             | 19                        | 90                     |
| Transect 2 | 38.60530, -<br>78.38418                 | 9810644                          | 17 Apr 2011          | 857                  | 272            | 19                        | 88                     |
| Transect 2 | 38.60336, -<br>78.38390                 | 9810626                          | 17 Apr 2011          | 887                  | 304            | 14                        | 94                     |
| Transect 2 | 38.60324, -<br>78.38360                 | 9810655                          | 17 Apr 2011          | 895                  | 345            | 13                        | 93                     |
| Transect 2 | 38.60163, -<br>78.38265                 | 9810657                          | 10 Apr 2011          | 950                  | 27             | 25                        | 90                     |
| Transect 2 | 38.60136, -<br>78.38288                 | 9810648                          | 10 Apr 2011          | 954                  | 245            | 21                        | 89                     |
| Transect 2 | 38.60003, -<br>78.38176                 | 9810664                          | 10 Apr 2011          | 996                  | 354            | 15                        | 83                     |
| Transect 2 | 38.59975, -<br>78.38176                 | 9810645                          | 10 Apr 2011          | 1002                 | 350            | 11                        | 86                     |
| Transect 2 | 38.59746, -<br>78.37986                 | 9810663                          | 10 Apr 2011          | 1047                 | 349            | 20                        | 89                     |
| Transect 2 | 38.59746, -<br>78.38010                 | 9810658                          | 10 Apr 2011          | 1053                 | 14             | 22                        | 89                     |
| Transect 3 | 38.54184, -<br>78.36692                 | 9810639                          | 3 Apr 2011           | 581                  | 61             | 22                        | 78                     |
| Transect 3 | 38.54161, -<br>78.36679                 | 9810659                          | 3 Apr 2011           | 596                  | 66             | 26                        | 78                     |
| Transect 3 | 38.54253, -<br>78.36916                 | 9810646                          | 3 Apr 2011           | 662                  | 45             | 40                        | 83                     |
| Transect 3 | 38.54339, -<br>78.36909                 | 9810633                          | 3 Apr 2011           | 667                  | 187            | 28                        | 72                     |

| <b>Location</b> | <b>Coordinates<br/>(latitude,<br/>longitude)</b> | <b>HOBO<br/>Identification<br/>Number</b> | <b>Installation<br/>Date</b> | <b>Elevation<br/>(m msl)</b> | <b>Azimuth<br/>(°)</b> | <b>Slope<br/>Steepness<br/>(°)</b> | <b>Canopy<br/>Cover<br/>(%)</b> |
|-----------------|--------------------------------------------------|-------------------------------------------|------------------------------|------------------------------|------------------------|------------------------------------|---------------------------------|
| Transect 3      | 38.54391, -<br>78.37228                          | 9810651                                   | 3 Apr 2011                   | 701                          | 32                     | 8                                  | 82                              |
| Transect 3      | 38.54442, -<br>78.37198                          | 9810640                                   | 3 Apr 2011                   | 709                          | 184                    | 22                                 | 77                              |
| Transect 3      | 38.54573, -<br>78.37417                          | 9810642                                   | 3 Apr 2011                   | 756                          | 205                    | 27                                 | 72                              |
| Transect 3      | 38.54615, -<br>78.37364                          | 9810666                                   | 3 Apr 2011                   | 761                          | 71                     | 28                                 | 68                              |
| Transect 3      | 38.54678, -<br>78.37584                          | 9810628                                   | 3 Apr 2011                   | 805                          | 188                    | 20                                 | 71                              |
| Transect 3      | 38.54732, -<br>78.37526                          | 9810631                                   | 3 Apr 2011                   | 806                          | 73                     | 29                                 | 66                              |
| Transect 3      | 38.54879, -<br>78.37740                          | 9810647                                   | 3 Apr 2011                   | 850                          | 96                     | 19                                 | 68                              |
| Transect 3      | 38.54934, -<br>78.37678                          | 9810632                                   | 3 Apr 2011                   | 855                          | 196                    | 11                                 | 70                              |
| Transect 3      | 38.55131, -<br>78.37911                          | 9810660                                   | 3 Apr 2011                   | 908                          | 175                    | 17                                 | 70                              |
| Transect 3      | 38.55120, -<br>78.37911                          | 9810652                                   | 3 Apr 2011                   | 909                          | 168                    | 11                                 | 72                              |
| Transect 3      | 38.55338, -<br>78.38127                          | 9810653                                   | 3 Apr 2011                   | 954                          | 76                     | 17                                 | 75                              |
| Transect 3      | 38.55310, -<br>78.38192                          | 9810630                                   | 3 Apr 2011                   | 956                          | 193                    | 17                                 | 60                              |
| Transect 3      | 38.55522, -<br>78.38341                          | 9810629                                   | 3 Apr 2011                   | 1001                         | 76                     | 10                                 | 70                              |
| Transect 3      | 38.55495, -<br>78.38360                          | 9810661                                   | 3 Apr 2011                   | 1002                         | 184                    | 16                                 | 73                              |

**Table 3b.** HOBO deployment locations, Cluster 1, as well as the installation date, on-site elevation, azimuth, slope steepness, and canopy cover. Position and elevation are obtained using in-situ measurements with a handheld GPS; azimuth, slope steepness, and canopy cover are obtained for each HOBO using 15 m spatial resolution USGS ArcGIS data bases.

| <b>Location</b> | <b>Coordinates<br/>(latitude,<br/>longitude)</b> | <b>HOBO<br/>Identification<br/>Number</b> | <b>Installation<br/>Date</b> | <b>Elevation<br/>(m msl)</b> | <b>Azimuth<br/>(°)</b> | <b>Slope<br/>Steepness<br/>(°)</b> | <b>Canopy<br/>Cover<br/>(%)</b> |
|-----------------|--------------------------------------------------|-------------------------------------------|------------------------------|------------------------------|------------------------|------------------------------------|---------------------------------|
| Cluster 1       | 38.55869, -<br>78.39113                          | 9923367                                   | 30 Jul 2011                  | 954                          | 25                     | 24                                 | 89                              |
| Cluster 1       | 38.55853, -<br>78.39106                          | 9923370                                   | 30 Jul 2011                  | 960                          | 12                     | 27                                 | 91                              |
| Cluster 1       | 38.55856, -<br>78.39114                          | 9823372                                   | 30 Jul 2011                  | 961                          | 17                     | 25                                 | 90                              |
| Cluster 1       | 38.55855, -<br>78.39113                          | 9923356                                   | 30 Jul 2011                  | 961                          | 17                     | 25                                 | 90                              |
| Cluster 1       | 38.55824, -<br>78.39032                          | 9990647                                   | 2 Jul 2011                   | 970                          | 16                     | 28                                 | 90                              |
| Cluster 1       | 38.55818, -<br>78.39027                          | 9990645                                   | 2 Jul 2011                   | 976                          | 19                     | 32                                 | 89                              |
| Cluster 1       | 38.55816, -<br>78.39042                          | 9990646                                   | 2 Jul 2011                   | 979                          | 15                     | 34                                 | 89                              |

| <b>Location</b> | <b>Coordinates<br/>(latitude,<br/>longitude)</b> | <b>HOB0<br/>Identification<br/>Number</b> | <b>Installation<br/>Date</b> | <b>Elevation<br/>(m msl)</b> | <b>Azimuth<br/>(°)</b> | <b>Slope<br/>Steepness<br/>(°)</b> | <b>Canopy<br/>Cover<br/>(%)</b> |
|-----------------|--------------------------------------------------|-------------------------------------------|------------------------------|------------------------------|------------------------|------------------------------------|---------------------------------|
| Cluster 1       | 38.55819, -<br>78.39047                          | 9990648                                   | 2 Jul 2011                   | 979                          | 15                     | 34                                 | 89                              |
| Cluster 1       | 38.55647, -<br>78.38765                          | 9923375                                   | 2 Jul 2011                   | 1030                         | 38                     | 12                                 | 84                              |
| Cluster 1       | 38.55644, -<br>78.38786                          | 9923363                                   | 2 Jul 2011                   | 1032                         | 35                     | 12                                 | 84                              |
| Cluster 1       | 38.55627, -<br>78.38757                          | 9923355                                   | 2 Jul 2011                   | 1033                         | 41                     | 11                                 | 84                              |
| Cluster 1       | 38.55629, -<br>78.38779                          | 9923362                                   | 2 Jul 2011                   | 1035                         | 41                     | 11                                 | 84                              |
| Cluster 1       | 38.55665, -<br>78.38832                          | 9923373                                   | 2 Jul 2011                   | 1036                         | 24                     | 13                                 | 88                              |
| Cluster 1       | 38.55656, -<br>78.38868                          | 9923360                                   | 2 Jul 2011                   | 1037                         | 14                     | 11                                 | 92                              |
| Cluster 1       | 38.55656, -<br>78.38846                          | 9923377                                   | 2 Jul 2011                   | 1037                         | 17                     | 12                                 | 90                              |
| Cluster 1       | 38.55651, -<br>78.38856                          | 9923360                                   | 2 Jul 2011                   | 1040                         | 16                     | 9                                  | 88                              |
| Cluster 1       | 38.55682, -<br>78.39108                          | 9923361                                   | 2 Jul 2011                   | 1052                         | 30                     | 22                                 | 88                              |
| Cluster 1       | 38.55687, -<br>78.39102                          | 9932266                                   | 2 Jul 2011                   | 1052                         | 30                     | 22                                 | 88                              |
| Cluster 1       | 38.55676, -<br>78.39117                          | 9823359                                   | 2 Jul 2011                   | 1055                         | 30                     | 23                                 | 86                              |
| Cluster 1       | 38.55674, -<br>78.39126                          | 9823371                                   | 2 Jul 2011                   | 1060                         | 33                     | 23                                 | 86                              |

The transects along the west-facing slope of SNP included 19 HOB0s. 14 of these were deployed along Skyland Fire Road, and 5 were deployed along Crusher Ridge Trail. Beginning at 1050 m msl along Skyland Fire Road, we deployed HOB0s in pairs, deploying one along the north-facing slope adjacent to Skyland Fire Road and another along the west-facing slope adjacent to Skyland Fire Road. We continued this every 50 m vertically to 750 m msl. Along Crusher Ridge Trail, HOB0s were deployed approximately every 100 m ascending the slope (rather than every 50 m because of limited resources), beginning at 1000 m msl.

All temperature sensors were enclosed in radiation shields to minimize radiative errors and were deployed adjacent to hiking trails to minimize disturbances to the area and for ease of access. Sensors recorded data on temperature and relative humidity at a frequency of once every ten minutes. To ensure that the sensors were functioning properly, all sensors were visited approximately once every two months to download data and to perform routine maintenance.

As of May, 2014, the network of HOB0 loggers is functional and still being maintained. Data through November, 2013 are available on a DVD (see the Appendix for more details). The data set

collected from the HOBO loggers is mostly complete, although there are sporadic gaps in the record that occur due one or more of the following reasons: 1) water short-circuiting the electronics, 2) damage by wildlife, and/or 3) difficulty establishing communication between the logger and computer used to download the data, which arose because we wanted to ensure that each logger was functioning properly in the field and thus we reset each logger after each data download. The average rate of data recovery for all HOBO loggers is about 80%. For the analyses associated and presented in this report, temperature logger data collected from 1 May 2011 through 31 August 2012 was utilized.

### **2.3.3. Temperature measurements in the habitat of *P. shenandoah***

In July, 2011, an additional 20 HOBO Pro V2 temperature-relative humidity loggers were deployed near Hawksbill. The objective of this deployment was to describe temperature variations within the five dominant vegetation types found within the habitat of *P. Shenandoah* (Table 4) (Young et al., 2006). The strategy was to deploy 4 HOBO loggers in each of the dominant vegetation types. HOBO loggers were deployed at approximately the same elevation and slope orientation to minimize the effects of elevation and aspect on temperature variations. Within each vegetation type, loggers were deployed approximately 10 m apart to assess microscale temperature variability.

**Table 4.** Dominant vegetation types within the habitat of *P. shenandoah*.

|                                                                        |
|------------------------------------------------------------------------|
| Central Appalachian Dry-Mesic Chestnut Oak - Northern Red Oak Forest   |
| Central Appalachian Northern Hardwood Forest                           |
| Northern Red Oak Forest (Pennsylvania Sedge - Wavy Hairgrass Type)     |
| Central Appalachian Montane Oak - Hickory Forest (Basic Type)          |
| Central Appalachian Dry Chestnut Oak - Northern Red Oak / Heath Forest |

## 2.4. Gridded Climate Data Sets

We use the observations to help evaluate pre-existing high-resolution gridded climate data sets: the Parameter-elevation Regressions on Independent Slopes Model (PRISM) and DAYMET, both of which we discuss in the present section.

### 2.4.1. *PRISM*

In Year I, we evaluated the performance of a high-resolution gridded climate data set in capturing the temperature variations at Big Meadows. PRISM, the Parameter-elevation Regressions on Independent Slopes Model (PRISM), uses point measurements of temperature and precipitation from long-term observation sites and interpolates these variables to high spatial resolutions using elevation, ocean proximity, and topographic facet. Topographic facets include multiple topographical features on a range of spatial scales, e.g. slope azimuth, the location of a point relative to the leeward or windward side of a mountain, etc. (e.g. Gibson et al., 1997; Daly et al., 2001; Daly et al., 2002). Based on the topographic facets for a selection of point climatological measurements, the climatological measurements are assigned different weightings when the climatological data are interpolated to a grid. The weightings are assigned based on how the topographic facets for the climatological stations compare with the surrounding topography, i.e. station measurements will be weighted more if the station's topographic facets are very similar to the surrounding area and less if they are very different [see Gibson et al., 1997 and Daly et al., 2001 for more details].

PRISM outputs two types of data sets using different averaging periods: 1) monthly climate data of mean monthly maximum temperature, mean monthly minimum temperatures, and total monthly precipitation from 1895 through the present for the contiguous US at a 4 km spatial resolution, and 2) 30-year monthly climate normals for monthly maximum temperature, monthly minimum temperature, and total monthly precipitation averaged over 1971-2000 (and, as of late 2012, 1981-2010) at an 800 m spatial resolution over the contiguous US (Daly et al., 2001; Daly et al., 2002). PRISM data are available at <http://prism.oregonstate.edu/>.

Both the 4 km and 800 m spatial resolutions of PRISM are too coarse to resolve temperatures at the spatial scale of the habitat of *P. shenandoah*. Thus, further downscaling of PRISM is necessary. To this end, in Year II, we developed a new approach to statistically downscale the 4 km PRISM monthly temperature data set using information obtained from the 800 m PRISM data set of 30-year monthly climate normals and evaluated its use in SNP. Within each 4 km monthly PRISM grid, there are 25 800-m PRISM grid cells that contain information about the historical temperature and about the elevation. We use this information to generate a lapse rate for each 4 km grid cell. Once

we have determined a lapse rate for each grid cell and for each month, the 4 km monthly temperature can be downscaled to any point within that grid box using the lapse rate, as long as the elevation of that point is known:

$$T_{Downscaled} = \overline{T_{4km}} + (Z_{4km} - Z_{DEM}) \cdot LR \quad (1)$$

where is  $T_{Downscaled}$  is the monthly temperature downscaled to a 15 m DEM,  $\overline{T_{4km}}$  is the mean PRISM-derived temperature for a given month in a 4 km grid box,  $Z_{4km}$  is the mean elevation of the 4 km grid box,  $Z_{DEM}$  is the elevation for each 15 m grid cell, and  $LR$  is the lapse rate, where a positive lapse rate indicates a decrease in temperature with height. A summary of this downscaling approach is shown in Figure 6. By standard meteorological convention, a positive lapse rate indicates a decrease in temperature with height.

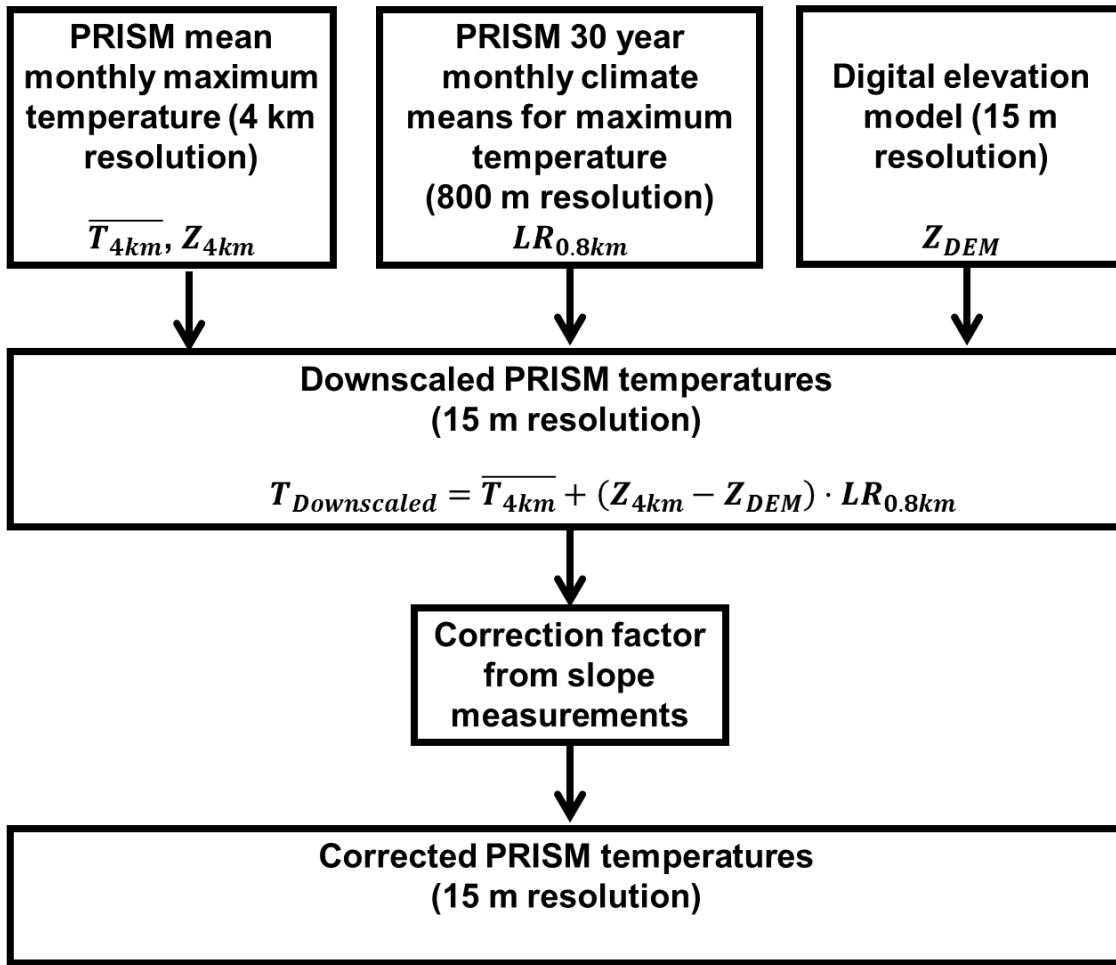


**Figure 6.** Summary of our downscaling method in which we downscale the monthly 4 km mean monthly maximum PRISM temperature ( $\overline{T_{4km}}$ ) to a 15 m resolution DEM based on the lapse rates derived from the 800 m PRISM 30 year monthly climate means for maximum temperature over the period 1971-2000 ( $LR_{0.8km}$ ) and the difference between the mean elevation of the 4 km grid box ( $Z_{4km}$ ) and elevation of each 15 m grid cell ( $Z_{DEM}$ ) to obtain downscaled PRISM ( $T_{Downscaled}$ ) at a 15 m resolution. We then apply a correction to  $T_{Downscaled}$  based on the slope temperature measurements to obtain more realistic, high-resolution estimates of temperature in Shenandoah National Park.

We evaluate this statistical downscaling approach using data from 1) long-term meteorological observations from Big Meadows and Pinnacles, and 2) temperature data from the network of HOBO temperature sensors deployed in spring, 2011. We then use this information to downscale both present-day temperatures, as well as projected, future temperature changes based on output from different GCM-RCM combinations that assume varying emissions scenarios, to a spatial scale of 15 m in SNP, using output from a digital elevation model (DEM). We choose a spatial scale of 15 m because this is a finest-scale topography data available for SNP.

#### **2.4.2. DAYMET**

Though we focus on downscaling PRISM in this report, we also show some results from other high-resolution gridded climate data sets that are presently available. In Year II and in Year III, we evaluated the performance of DAYMET (Thornton et al., 1997). DAYMET outputs daily maximum and minimum temperature at a 1 km grid for the years 1980-2011. These data are available from [http://www.DAYMET.ornl.gov/custom\\_home](http://www.DAYMET.ornl.gov/custom_home).

Because DAYMET does not have a data set including 30 year climate normals like PRISM does, we have to generate this data set ourselves by determining the mean monthly maximum temperature over the period 1980-2011 for each grid box. We then use this information to determine a monthly lapse rate that is specific to that grid cell. This lapse rate is based on information obtained from 25 temperature-elevation pairs to be consistent with PRISM. Following the procedure enumerated earlier, these monthly lapse rates are used to statistically downscale DAYMET mean monthly maximum temperatures to individual point measurements.

## **2.5. High-resolution simulations with a mesoscale meteorological model**

In Year III, we completed simulations using the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008). WRF is a state-of-the-art mesoscale meteorological model that we run using initial conditions provided from the North American Regional Reanalyses (NARR) (Mesinger et al., 2006). We first evaluate the model's ability to capture present-day temperature variations in SNP and then use the model to dynamically downscale climate model output to SNP. Using WRF to dynamically downscale climate model output is not straightforward because of the computational demands. For example, each month-long simulation discussed in this report took about 3 days to run using a cluster with 64 processors (see Section 3.2.3 for more details). The aforementioned statistical downscaling approaches are nowhere near as computationally demanding.

## **2.6 Regional climate model results**

We use output from the NARCCAP program [see <http://www.narccap.ucar.edu/> for a full description] and evaluate 7 NARCCAP GCM-RCM pairs (Table 5). NARCCAP models use the SRES A2 emissions scenario, which assumes moderate emissions, and have a 50 km spatial resolution over North America. Model output is available for two 30-year time periods: 1971-2000 and 2041-2070. We evaluate a suite of NARCCAP GCM-RCM pairs using temperature data from Big Meadows.

### **2.6.1. NARCCAP**

We use output from the NARCCAP program [see <http://www.narccap.ucar.edu/> for a full description] and evaluate 7 NARCCAP RCMs (Table 5). NARCCAP models use the SRES A2 emissions scenario, which assumes moderate emissions, and have a 50 km spatial resolution over North America. Model output is available for two 30-year time periods: 1971-2000 and 2041-2070. We evaluate a suite of NARCCAP RCMs using temperature data from Big Meadows.

**Table 5.** NARCCAP GCM-RCM pairs evaluated in this study.

| <b>NARCCAP Model (GCM-RCM)</b>                                           | <b>Abbreviation (GCM-RCM)</b> |
|--------------------------------------------------------------------------|-------------------------------|
| Community Climate System Model-Canadian Regional Climate Model           | CCSM-CRCM                     |
| Coupled General Circulation Model-Canadian Regional Climate Model        | CGCM-CRCM                     |
| Community Climate System Model-Weather Research and Forecasting Model    | CCSM-WRFG                     |
| Coupled General Circulation Model-Weather Research and Forecasting Model | CGCM-WRFG                     |
| Geophysical Fluid Dynamics Model-Hadley Regional Model Version 3         | GFDL-HRM3                     |
| Coupled General Circulation Model-Regional Climate Model Version 3       | CGCM-RCM3                     |
| Geophysical Fluid Dynamics Model-Hadley Regional Model Version 3         | GFDL-HRM3                     |

### **2.6.2. Other regional climate models**

Because NARCCAP projections only assume one emissions scenario, we use output from other RCMs. In Year II, we evaluated downscaled climate model output obtained from Jacob Sewall at Kutztown University. The NCAR CCSM (e.g. Gent et al., 2011) provides boundary conditions that are used to project climate change estimates to the Mid-Atlantic region at a 10 km spatial resolution using the Regional Climate Model Version 3 (RegCM3) [see <<http://users.ictp.it/~pubregcm/> for more information]. The three different emissions scenarios make different assumptions about changes in atmospheric CO<sub>2</sub> (IPCC, 2007):

Committed Climate Change: assumes Year 2000 greenhouse gas concentrations, i.e. ~370 ppm (IPCC, 2007)

SRES B1: a moderate climate change scenario which assumes atmospheric CO<sub>2</sub> mixing ratios will stabilize around 550 ppm in Year 2100 (IPCC, 2007)

SRES A1FI: a more pessimistic climate change scenario which assumes CO<sub>2</sub> emissions will stabilize in Year 2080 but will exceed 1000 ppm in Year 2100 (IPCC, 2007)



## Results and Discussion

In this section, we first discuss recent climate variability in SNP based on the long-term observations from Big Meadows. We then discuss spatiotemporal temperature variability in SNP using our observations from the network of HOBO loggers and use these observations to evaluate our downscaling approaches. We then use the data from the observations to apply correction factors to the downscaled RCM output.

We focus on the summer months when *P. shenandoah* is most active, specifically July because *P. shenandoah* is expected to exhibit a greater response to changes in summer extremes in maximum temperature than to changes in minimum temperature (E.H.C. Grant, personal communication). However, we also show some results from January to show the sensitivity of our downscaling approach to seasonal extremes. We focus on maximum temperatures instead of minimum temperatures because *P. shenandoah* is expected to exhibit a greater response to changes in maximum temperatures than to changes in minimum temperature (E.H.C. Grant, personal communication). However, when we discuss output from the RCMs, we also include some discussion of minimum temperature for completeness and to understand how trends in minimum temperatures compare with trends in maximum temperatures.

Quantifying atmospheric moisture (i.e. dew point or relative humidity) and precipitation at the same spatial scales as maximum temperature is more difficult. This difficulty arises because 1) gridded relative humidity, dew point, and precipitation are not available at the same high spatial resolutions as temperature in PRISM (e.g. Daly et al., 2001), and 2) the relationship between atmospheric moisture and elevation is much more complicated than it is for temperature.

Though we do not explicitly present a methodology to downscale humidity or precipitation in the present report, we do use WRF to investigate current spatial patterns in relative humidity (c.f. Section 3.2.3). We focus on the mean relative humidity instead of minimum relative humidity to characterize atmospheric moisture content because the minimum relative humidity is simply a function of the daily maximum temperature. In addition to presenting present-day analyses of relative humidity and total monthly precipitation, we discuss output from multiple RCMs that illustrate the large uncertainties in projected changes in total monthly precipitation in the Mid-Atlantic region and southeast US (c.f. Section 3.4)

### 3.1. Present-day temperature variations in SNP

To understand present-day temperatures in SNP, we discuss long-term climate trends at Big Meadows, as well as the observations from our network of HOBO temperature-relative humidity sensors, in the present section.

### **3.1.1. Long-term temperature trends in SNP**

Significant inter-decadal variability is observed in the Big Meadows temperature record that is consistent with climate trends at other climate stations in the southeast US (e.g. Saxena and Menon, 1999; Rogers, 2013) and Mid-Atlantic region (e.g. Polsky et al., 2000). Mean annual temperatures at Big Meadows cooled by about 2°C during the middle 20<sup>th</sup> century; since 1980, however, mean annual temperatures have been increasing (Figure 7a). Overall, though, there is a statistically significant negative trend in mean annual temperature between 1935 and 2010 ( $r=-0.35$ ,  $p<0.01$ ). Mean July maximum temperatures show a slight upward trend between 1970 and 1990 (Figure 7b). Following a cooling trend in the mid-late 1990s, mean July maximum temperatures continue to increase, but the trend over the period 1935-2010 is not statistically significant ( $r=-0.14$ ,  $p=0.25$ ). Total annual precipitation shows a slight upward trend, but exhibits significant inter-annual variability (Figure 7c). Even so, there is a positive upward trend ( $r=0.34$ ,  $p<0.01$ ) from 1935-2010.

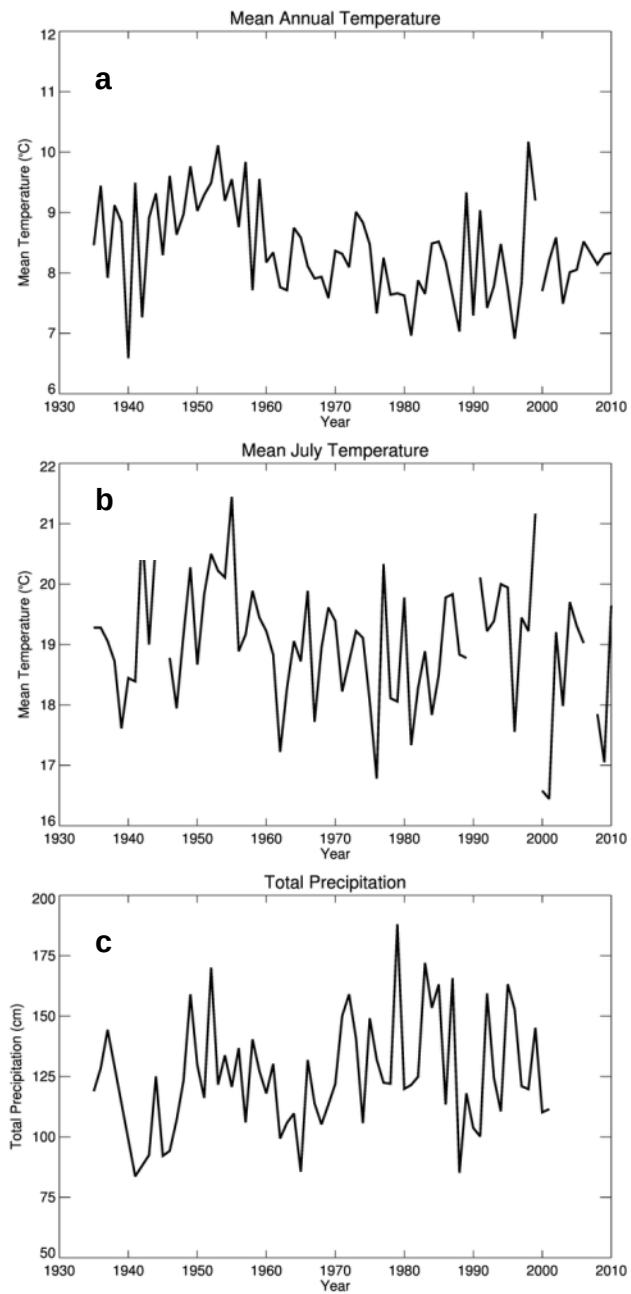


**Figure 7.** Mean annual temperature (a), mean July maximum temperature at Big Meadows (b), and total annual precipitation (c) at Big Meadows, 1935-2010. Only years and months with >75% data completion are shown.

### 3.1.2. Relationship between Big Meadows and measurements within the habitat of *P. shenandoah*

As displayed in the July 2012 data below, mean maximum temperatures 2 m agl at Big Meadows are on average 2-3°C warmer than temperatures experienced within the different vegetation types that comprise the Hawksbill habitat (Figure 8a). This difference can partly be explained by the difference in elevation, with Big Meadows 50-100 m higher in elevation than the HOBOs deployed at Hawksbill, as well as the specific topographic characteristics of the HOBO locations within the habitat of *P. shenandoah* characterized by shaded, vegetated north-facing slopes (Figure 8). This offset is fairly consistent among the different vegetation types within the habitat of *P. shenandoah*, with no significant differences in this relationship among the different vegetation types. The difference is larger when temperatures are warmer (i.e. the summer months) and smaller in the winter, when differences between Big Meadows and the habitat of *P. shenandoah* are within 1°C (Figure 9). Because of the higher daily maximum temperatures at Big Meadows and because the monitoring site at Big Meadows is located in an open field whereas the HOBO loggers were deployed in moister, forested sites, the mean daily relative humidity at Big Meadows is typically lower than what is experienced within the habitat of *P. shenandoah* (Figure 8b, Figure 10).

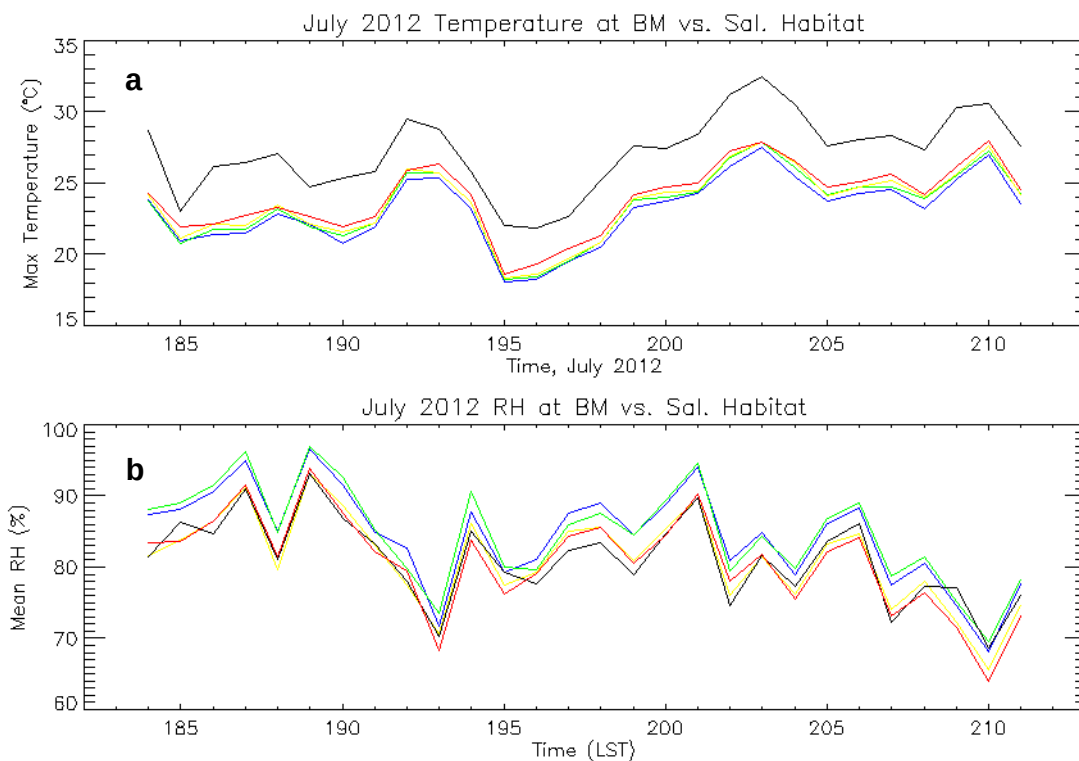


**Figure 8.** Relationship between mean daily maximum temperature (a) and mean daily relative humidity (b) at Big Meadows (black) and the temperatures observed in different vegetation types within the habitat of *P. shenandoah*: Central Appalachian dry-mesic chestnut oak-northern red oak forest (red), Central Appalachian northern hardwood forest (blue), northern red oak forest (yellow), Central Appalachian montane oak-hickory forest (green), and Central Appalachian Dry chestnut oak (orange). July, 2012 is shown as an example.

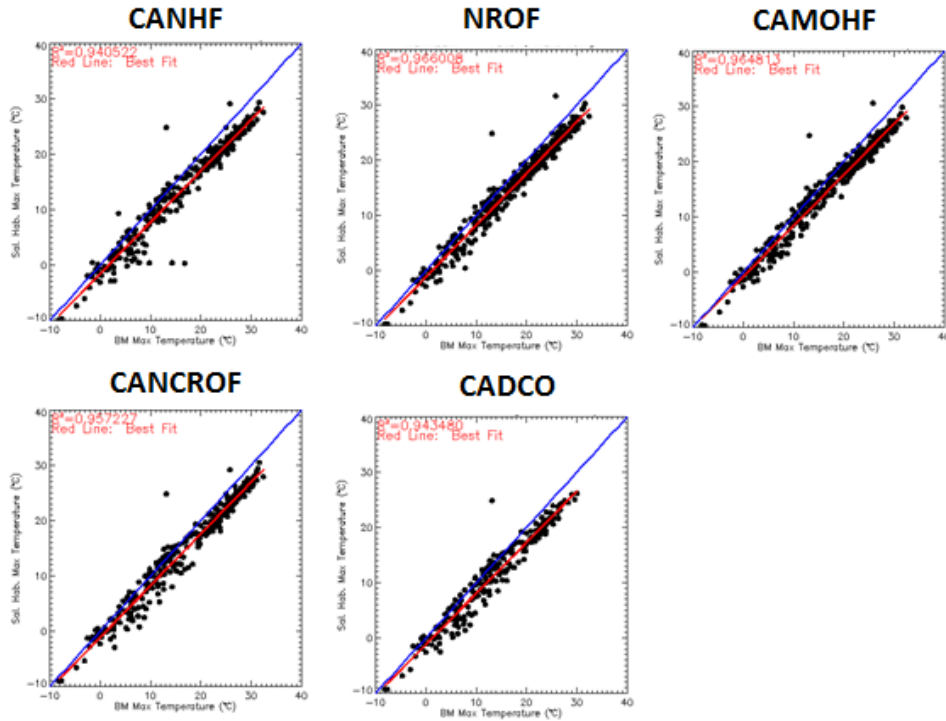


**Figure 9.** Relationship between temperature observations at Big Meadows and those within different vegetation types within the habitat of *P. shenandoah* (CADCROF: Central Appalachian dry-mesic chestnut oak-northern red oak forest, CANHF: Central Appalachian northern hardwood forest, NROF: northern red oak forest, CAMOHF: Central Appalachian montane oak-hickory forest, CADCO: Central Appalachian Dry chestnut oak) for mean daily maximum temperature. Red and blue line represent line of best fit (y-intercept not set to 0) and 1:1 line, respectively.  $R^2$  shown in top left of each panel. Data for the first year of measurements (1 May 2011 – 30 April 2012) shown.

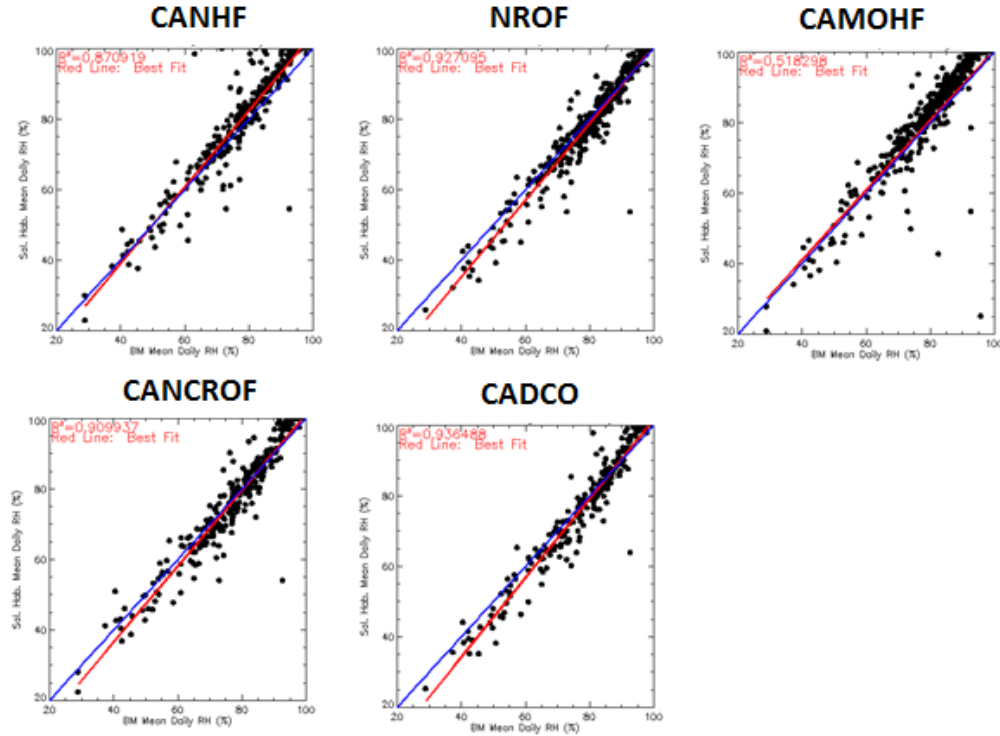


**Figure 10.** Relationship between mean daily relative humidity observations at Big Meadows and those within different vegetation types within the habitat of *P. shenandoah* (CADCROF: Central Appalachian dry-mesic chestnut oak-northern red oak forest, CANHF: Central Appalachian northern hardwood forest, NROF: northern red oak forest, CAMOHF: Central Appalachian montane oak-hickory forest, CADCO: Central Appalachian Dry chestnut oak). Red and blue line represent line of best fit and 1:1 line, respectively.  $R^2$  shown in top left of each panel. Data for the first year of measurements (1 May 2011 – 30 April 2012) shown.

Since the temperature differences between Big Meadows and the habitat of *P. shenandoah* are largest in the summer months than in the winter months, it may be that differences in canopy cover between the monitoring site at Big Meadows and the locations where the HOBO loggers were deployed is driving these differences. The presence of shading by the canopy in the locations where many of the HOBOs were deployed result in less incoming shortwave radiation reaching the surface than in open, grassy areas like Big Meadows. At open areas like Big Meadows, larger amounts of incoming radiation can create microclimates inside the naturally ventilated radiation shields used in this study and result in measured temperatures that have been found to be 2-3°C higher than would be observed if the sensors were mechanically aspirated (e.g. Nakamura and Mahrt, 2005). These warm biases, or radiation errors, are most pronounced under periods of strong insolation and weak winds. We expect that these warm biases are lower in regions with greater canopy coverage, e.g. the areas in which many of the slope HOBOs were deployed. The canopy coverage in these areas is >70%, whereas the monitoring site at Big Meadows is located within a grassy field as specified by WMO (World Meteorological Organization) standards with no canopy cover. These differences suggest that canopy cover is one of the important drivers of near-surface temperature variability. The effects of canopy

cover on temperature become more apparent when we compare the observed temperatures from the HOBO network with downscaled temperatures using PRISM and are incorporated into an empirical correction factor that we develop in Section 3.2.

### 3.1.3. Temperature and relative humidity variability within habitat of *P. shenandoah*

We find that mean July maximum temperature has the largest variability within the boulderfields, with differences among the 4 loggers of  $0.6^{\circ}\text{C}$  that are generally consistent year-to-year (Figure 11). Temperature differences within the other three vegetation types are  $<0.2^{\circ}\text{C}$  and within the stated accuracy of the HOBO loggers ( $\pm 0.2^{\circ}\text{C}$ ).

In addition, temperatures within the boulderfield are also about  $0.7^{\circ}\text{C}$  warmer than the other 3 vegetation types because the elevation of the boulderfield is about 100 m lower. Differences in temperature between the montane oak-hickory forest and northern red oak forest are within the stated accuracy of the HOBO loggers, whereas temperatures in the northern hardwood forest are about  $0.5^{\circ}\text{C}$  cooler than the montane oak-hickory forest and northern red oak forest.

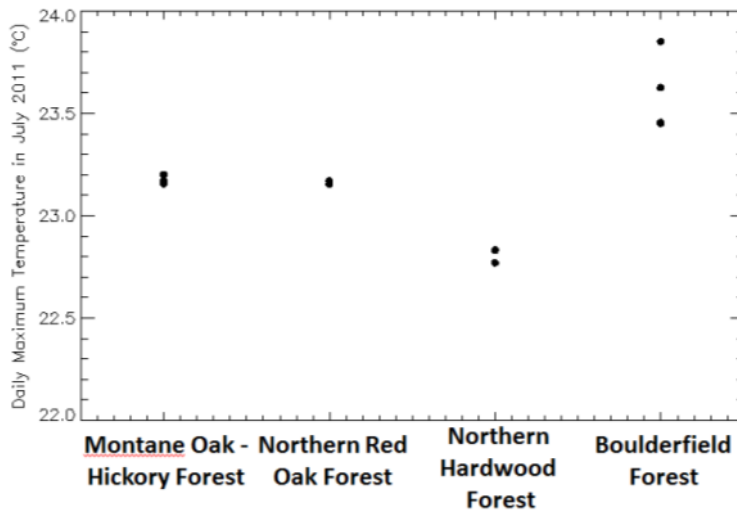


**Figure 11.** Mean maximum temperatures within the 4 dominant vegetation types that occur in the habitat of *P. shenandoah*. July 2012 is shown as an example. Note that the boulderfields include the Central Appalachian dry-mesic chestnut oak-northern red oak forest (CADCROF) and Central Appalachian Dry chestnut oak (CADCO).

To determine if these differences occur because of vegetation or if these differences are simply due to differences in elevation, we use the lapse rate in July maximum temperature along the west slope

of the Blue Ridge ( $7^{\circ}\text{C km}^{-1}$ ) and compare the temperatures expected assuming this lapse rate with the mean temperatures observed within the four different vegetation types that occur within the habitat of *P. shenandoah* (Figure 12). We find that, when we account for the expected temperature differences that occur because the vegetation types are located at different elevations, the mean maximum temperatures are within the stated accuracy of the HOBO loggers. Thus, we conclude that vegetation type is not a strong driver of temperature variability within the habitat of *P. shenandoah* and do not incorporate tree species as an input into our downscaling approach.

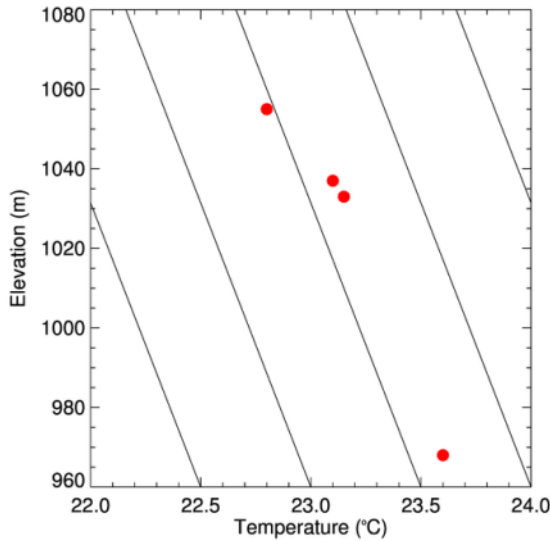


**Figure 12.** Elevation of the four dominant vegetation types within the habitat of *P. shenandoah* as a function of mean July maximum temperature within the four habitats (red circles). Black lines every  $0.5^{\circ}\text{C}$  represent mean lapse rate in July maximum temperature ( $7^{\circ}\text{C km}^{-1}$ ). July 2012 is shown as an example.

### 3.1.4. Slope temperature measurements

We use data from the three transects (c.f. Figure 5, Table 2) to evaluate our statistical downscaling approaches. For this project, we focus on maximum temperatures and mean relative humidity which are expected to have important impacts on the distribution of *P. shenandoah*. We determine mean monthly lapse rates in maximum temperature along the eastern and western sides of the Blue Ridge. We find that monthly lapse rates range from  $4\text{--}8^{\circ}\text{C km}^{-1}$ , with lapse rates smallest in December and January and steepest in July and August (Figure 13). On both sides of the Blue Ridge, these lapse rates are consistently smaller than the dry adiabatic lapse rate ( $9.8^{\circ}\text{C km}^{-1}$ ) but much closer to the standard atmospheric lapse rate ( $6.5^{\circ}\text{C km}^{-1}$ ).

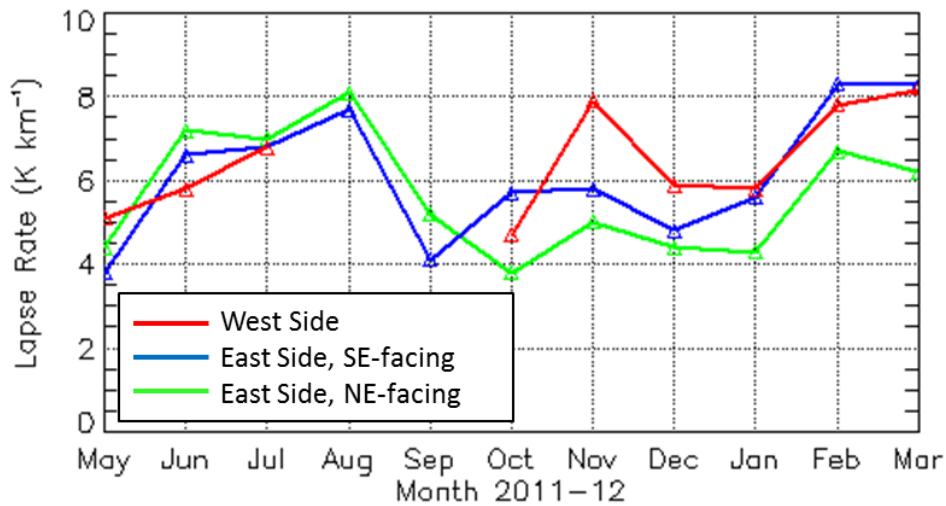


**Figure 13.** Variations in lapse rate by month for the first year of measurements (April 2012 not shown due to incomplete data records along all three trails) along the west side of the Blue Ridge (red line), southeast-facing slope along the east side of the Blue Ridge (blue line), and northeast-facing slope along the east side of the Blue Ridge (green line) for the first year of measurements. Only months with >75% data completion are shown.

We also investigate the role of slope azimuth on our temperature measurements using data from the Cedar Run Trail along the east side of SNP. We find that the HOBOs deployed along the southeast-facing slopes recorded a mean monthly maximum temperature that was on average  $0.5 \pm 0.3^\circ\text{C}$  warmer in July than the adjacent HOBO deployed along the northeast-facing slope (Figure 14). Differences between the HOBO pairs were largest in the winter when the mean difference between the pairs was  $0.9^\circ\text{C} \pm 0.3^\circ\text{C}$ . The presence of canopy cover during the warm season helps to shield the surface from incoming solar radiation and results in the slope azimuth having a smaller impact on near-surface temperature during the warm season than during the cool season. During the cool season when there is much less canopy cover, the effects of slope azimuth on near-surface temperature are larger.

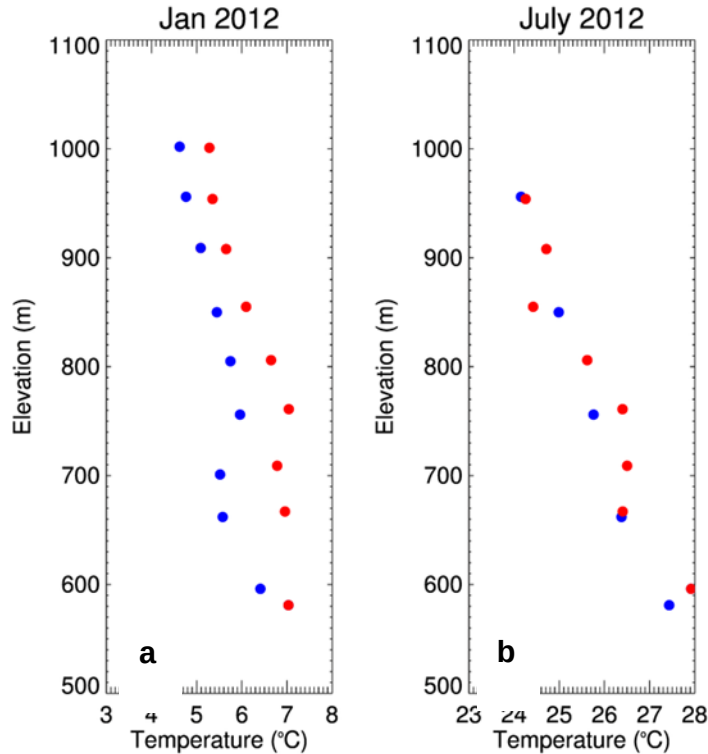


**Figure 14.** Elevation as a function of mean monthly maximum temperature in January 2012 (a) and July 2012 (b) along Cedar Run Trail. HOBOS located along the southeast- and northeast-facing slopes are indicated by red and blue circles, respectively. Note that data were missing for the southeast-facing HOBOS logger located near 700 m msl and for the southeast-facing HOBOS logger located near 900 m msl in July, 2012.

### 3.2. Evaluation of downscaling methods

In this section, we evaluate our statistical and dynamical downscaling methods. We focus on mean July maximum temperature but also shown some examples from other seasons to show the sensitivity of our downscaling approach to seasonal extremes. The statistical downscaling methods using PRISM and DAYMET are evaluated in sections 3.2.1 and 3.2.2, respectively, and the dynamical downscaling method using WRF is evaluated in section 3.2.3.

#### 3.2.1. PRISM Evaluation

Year-round mean monthly maximum PRISM-derived temperatures for the period 1971-2000 show strong correlation with 2 m agl temperatures at Big Meadows obtained from the NCDC ( $r=0.99$ ,  $p<0.01$ ). However, PRISM overestimates maximum temperatures at Big Meadows by  $2.6^{\circ}\text{C}$  (Figure 15). The mean elevation of the grid cell containing Big Meadows in PRISM is about 200 m lower

than actual elevation of the Big Meadows weather station (873 m vs. 1079 m), which partly explains this warm bias. When we apply our statistical downscaling approach (see section 2.4), we find that the mean bias error is reduced by about 50%.

We do the same for temperatures measured 2 m agl at Pinnacles using the 5 year data set. The elevation of the grid box in PRISM containing Pinnacles is 927 m, i.e. about 100 m lower than Pinnacles' actual elevation. Within the 5 year data record, mean monthly maximum temperatures within the grid box containing Pinnacles are overestimated by 2.9°C. Applying our statistical downscaling approach to the PRISM data set does not remove as much bias as for Big Meadows. The mean bias error is reduced only to 2.3°C with the application of this downscaling approach. One reason for the poorer comparison for Pinnacles than for Big Meadows may be related to differences in canopy cover. The larger canopy cover at Pinnacles than at Big Meadows may reduce the surface temperature at Pinnacles compared to Big Meadows. This explanation is supported by our finding that the presence of more canopy cover during the warm seasons increases the MBE, as we will discuss next.

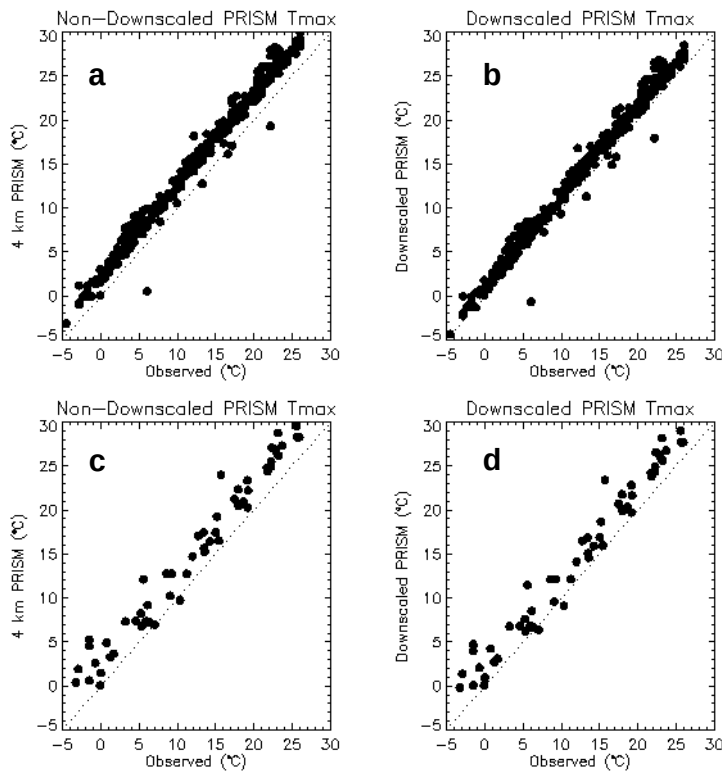


**Figure 15.** Relationship between mean monthly maximum temperatures observed at Big Meadows and PRISM-derived mean monthly maximum temperature for the grid box containing Big Meadows 1971-2010 (a) (N=369). Same for top right panel, but using downscaled PRISM (b). Mean bias error (MBE) for non-downscaled and downscaled PRISM is 2.6°C and 1.3°C, respectively. Same for (c) and (d) but for Pinnacles measurements, which are available July 2008 through May 2013 (N=53). Only months with data completion >75% are shown. MBE=2.9°C and 2.3°C, respectively. Dotted line is 1:1 line.

When we evaluate our statistical downscaling approach using data from the network of HOBOS deployed along the west and east sides of the Blue Ridge, we find that the downscaling approach does not work as well as it does for Pinnacles or for Big Meadows. We find that PRISM overestimates mean July maximum temperature by 2–4°C in 2011, though this is still generally better than making the correction using the dry adiabatic lapse rate (9.8 K km<sup>-1</sup>) or environmental lapse rate (6.5 K km<sup>-1</sup>) (Figure 16, Table 6). The overestimates in mean maximum temperature occur independently of elevation but are instead driven by differences between the east side and west side of the Blue Ridge Mountains. The largest differences are along the cooler eastern side of the Blue Ridge Mountains, where mean July maximum temperatures are overestimated by 4.2°C. We find similar results in July, 2012; the model overestimates mean July maximum temperature along the east slope and west slope by 3.4°C and 2.1°C, respectively. The overestimates are larger in the summer than in the winter, when overestimates are typically about 1°C. During the winter, the stronger bias along the east slope is removed. As we concluded in the previous section, the differences between the summer and winter may be due to differences in canopy cover that PRISM is not incorporating.

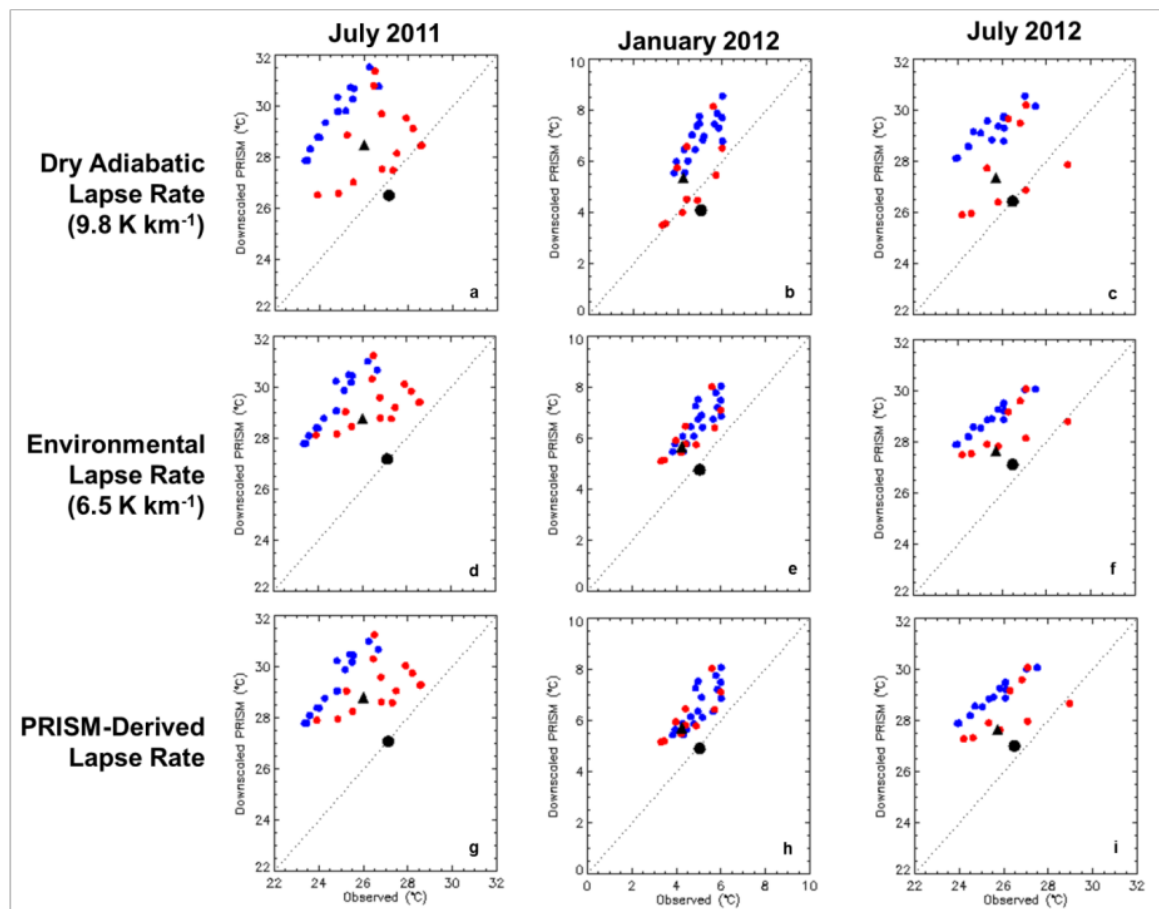


**Figure 16.** Comparison between observed temperature from HOBOS and statistically downscaled temperatures for July, 2011; January, 2012; and July, 2012 assuming a dry adiabatic lapse rate (9.8 K km<sup>-1</sup>) (panels a-c), environmental lapse rate (6.5 K km<sup>-1</sup>) (panels d-f), and PRISM-derived lapse rate (panels g-i). Red dots indicate west slope, blue dots indicate east slope. Black triangle and black circle represent Pinnacles and Big Meadows, respectively. Dotted line is 1:1 line.

**Table 6.** Mean bias error (MBE) in July, 2011; January, 2012; and July, 2012 along the west slope and west slope assuming different lapse rates.

| <b>Lapse Rate</b>                     | <b>July 2011<br/>MBE(°C)</b> | <b>January<br/>2012<br/>MBE(°C)</b> | <b>July<br/>2012<br/>MBE(°C)</b> |
|---------------------------------------|------------------------------|-------------------------------------|----------------------------------|
| Dry Adiabatic Lapse Rate (West Slope) | 1.79                         | 0.62                                | 1.51                             |
| Dry Adiabatic Lapse Rate (East Slope) | 4.82                         | 1.88                                | 3.67                             |
| Environmental Lapse Rate (West Slope) | 2.56                         | 1.48                                | 2.23                             |
| Environmental Lapse Rate (East Slope) | 4.54                         | 1.60                                | 3.39                             |
| PRISM-Derived Lapse Rate (West Slope) | 2.45                         | 1.51                                | 2.13                             |
| PRISM-Derived Lapse Rate (East Slope) | 4.53                         | 1.48                                | 3.38                             |

Also important to note is that the mean bias error for the statistically downscaled PRISM temperatures is smaller along the west slope of the Blue Ridge than along the east slope of the Blue Ridge. This may be a function of the more linear nature of the slope along the east side of the Blue Ridge along which HOBOS were deployed. As shown in Figure 5, the HOBOS were deployed along nearly a straight line extending downward along the Cedar Run drainage (c.f. Figure 5c), whereas the HOBOS along the west slope of the Blue Ridge were deployed along a non-linear transect simply because the Skyland Fire Road and Crusher Ridge Trails are also non-linear (c.f. Figure 5a, Figure 5b), resulting in exposure to more different topographical facets along the west side of SNP than along the east side of the Blue Ridge (c.f. Table 3a).

Based on results above, we used an additional correction factor to more accurately downscale PRISM mean monthly maximum temperatures. This correction factor empirically accounts for the discrepancy between the model and observations to give a more realistic representation of present mean monthly maximum temperatures within SNP. For July, 4°C should be subtracted from the downscaled values along the east side of the Blue Ridge, and 2°C should be subtracted from the downscaled values along the west side of the Blue Ridge to yield a more realistic approximation of the temperatures observed in SNP. This use of this correction factor significantly reduces the MBE (Figure 17). Note that this empirical correction factor can only be applied to the maximum temperatures in July. For this reason, we also provide a list of correction factors for each month for the east and west slopes of the Blue Ridge that are largely seasonally-dependent (Table 7) because of changes in the foliage density with season.

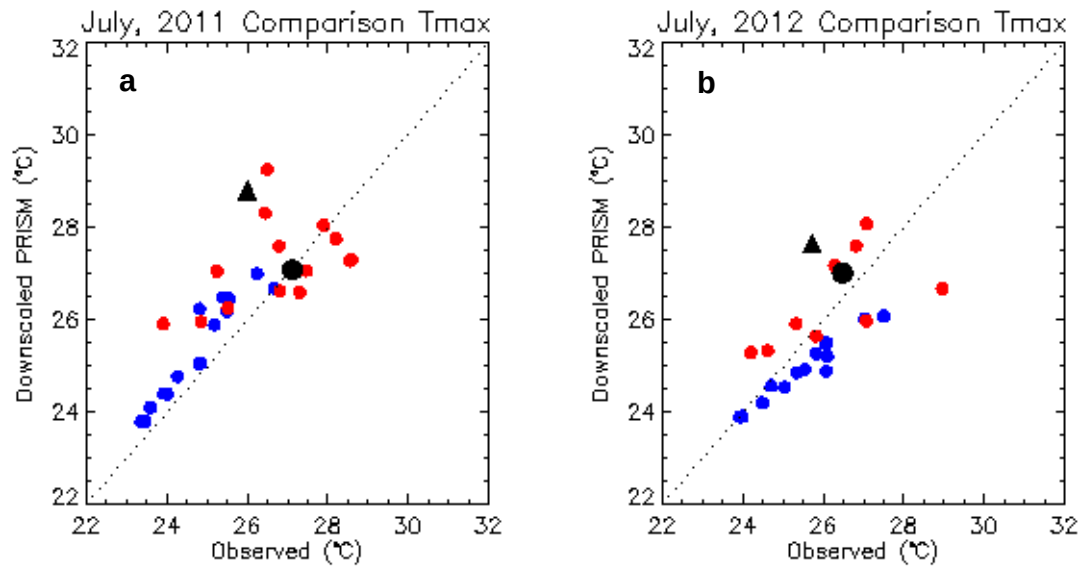


**Figure 17.** Comparison between observed temperature from HOBOS and downscaled temperatures from statistically downscaled PRISM for July 2011 (a) and July 2012 (b), but using a correction factor of 2°C (4°C) for sites along the west (east) slope of the Blue Ridge. No correction factor applied for mountaintop stations (i.e. Pinnacles and Big Meadows). Red dots indicate west slope, blue dots indicate east slope. Black triangle and black circle represent Pinnacles and Big Meadows, respectively. Dotted line is 1:1 line. For July, 2011, MBE for the west (east) slope is 0.45°C (0.53°C); in July, 2012, MBE for the west (east) slope is 0.13°C (-0.62°C).

**Table 7.** Correction factor that should be applied to PRISM as a function of month for the west and east slopes of the Blue Ridge. A correction factor is unavailable for April due to incomplete data record in April, 2012.

| Month | Correction Factor,<br>West Slope (°C) | Correction Factor,<br>East Slope (°C) |
|-------|---------------------------------------|---------------------------------------|
| Jan   | 1.5                                   | 1.5                                   |
| Feb   | 2.5                                   | 3.4                                   |
| Mar   | 2.0                                   | 3.6                                   |
| Apr   | XXX                                   | XXX                                   |
| May   | 2.2                                   | 3.8                                   |
| Jun   | 2.5                                   | 4.0                                   |
| Jul   | 2.0                                   | 4.0                                   |
| Aug   | 3.4                                   | 4.7                                   |
| Sep   | 3.7                                   | 3.8                                   |
| Oct   | 2.9                                   | 3.9                                   |
| Nov   | 1.3                                   | 1.7                                   |
| Dec   | 1.4                                   | 1.8                                   |

The correction factor discussed above, however, only considers whether a location is to the east or to the west of the Blue Ridge. Our results from the temperature sensors deployed along Cedar Run Trail suggest that an additional correction factor is needed to account for differences in azimuth. We found a  $0.5^{\circ}\text{C}$  difference in mean monthly maximum July temperature between the northeast-facing slopes and southeast-facing slopes, with larger differences occurring in the winter months due to the absence of vegetation cover in these months. For this reason, we impose an empirical offset of  $0.5^{\circ}\text{C}$  higher temperatures along slopes with a southward orientation (i.e. between  $135^{\circ}$  and  $225^{\circ}$ ), regardless of the location of the site along the east side or west side of SNP which results in better agreement between the model and observations (Figure 18). These correction factors are summarized in Table 8.

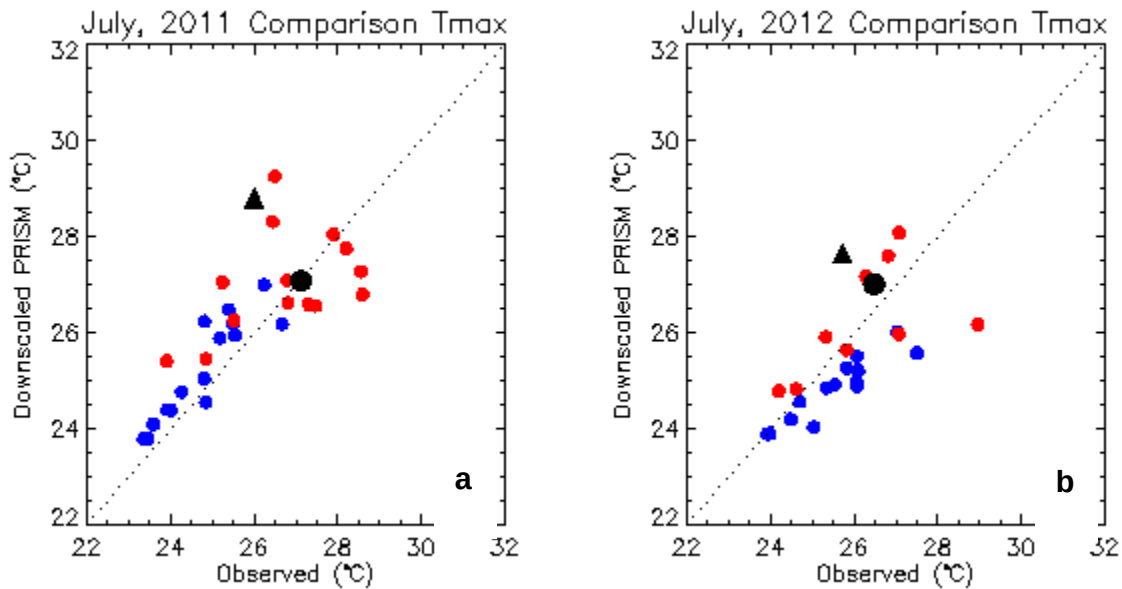


**Figure 18.** Comparison between observed temperature from HOBOS and downscaled temperatures from PRISM for July 2011 (a) and July 2012 (b), but using 1) a correction factor of  $2^{\circ}\text{C}$  ( $4^{\circ}\text{C}$ ) for sites along the west (east) slope of the Blue Ridge, and 2) a  $0.5^{\circ}\text{C}$  temperature offset for southward-oriented (between  $135^{\circ}$  and  $225^{\circ}$ ) slopes. No correction factor applied for mountaintop stations (i.e. Pinnacles and Big Meadows). Red dots indicate west slope, blue dots indicate east slope. Black triangle and black circle represent Pinnacles and Big Meadows, respectively. Dotted line is 1:1 line. For July, 2011, MBE for the west (east) slope is  $0.27^{\circ}\text{C}$  ( $0.44^{\circ}\text{C}$ ); in July, 2012, MBE for the west (east) slope is  $0.041^{\circ}\text{C}$  ( $0.53^{\circ}\text{C}$ ).

**Table 8.** Summary of empirical correction factors applied to downscaled PRISM mean monthly maximum temperature for July.

| Slope                                                            | Correction Factor to<br>Downscaled PRISM (°C) for<br>July |
|------------------------------------------------------------------|-----------------------------------------------------------|
| West slope of Blue Ridge,<br>Slope oriented to south (135°-225°) | 1.5                                                       |
| West slope of Blue Ridge,<br>Slope not oriented to south         | 2.0                                                       |
| East slope of Blue Ridge,<br>Slope oriented to south (135°-225°) | 3.5                                                       |
| East slope of Blue Ridge,<br>Slope not oriented to south         | 4.0                                                       |

Despite these corrections that we propose, it is important to note several caveats when these correction factors are applied:

1. Whereas the effects of canopy cover were found to be important when comparing temperatures at Big Meadows with temperatures in the habitat of *P. shenandoah* and in summer versus winter, the effects of these differences are not explicitly quantified but instead incorporated into the empirical correction factors stated in Table 8. We would need detailed information about monthly changes in canopy cover at high resolution, but we do not have this information.
2. None of the slopes for which we did these analyses was located either directly north or directly south because of limited resources. Thus, temperatures on true north (south) facing slopes may be even cooler (warmer) than indicated by the correction factors noted above.
3. We do not consider shading that might occur by an adjacent mountain ridge, which may also have significant impacts on temperature (e.g. Whiteman, 2000).
4. These correction factors have been developed explicitly for SNP. As of December, 2013, they have not been tested outside of SNP and thus should not be applied to regions outside the boundaries of SNP.
5. The correction factors have been developed using only 2 years of data and could be more robust with a longer data record.

### **3.2.2. DAYMET Evaluation**

To show the sensitivity of our downscaling approach to other high-resolution gridded climate data sets, we present a selection of results from downscaled DAYMET.

We find that mean monthly maximum temperatures from DAYMET are on average 1-2°C higher than PRISM-derived downscaled temperatures. For this reason, downscaled DAYMET temperatures have an even larger bias than the downscaled PRISM temperatures. The same trends emerge when we compare the east slope of the Blue Ridge with the west slope of the Blue Ridge. The largest differences are along the cooler eastern slope (Figure 19), where mean July maximum temperatures are overestimated by as much as 6°C compared to about 4°C along the west slope of the Blue Ridge. Differences are lower during the winter. Because the differences are larger with DAYMET than PRISM, we use PRISM instead of DAYMET to downscale maximum temperatures.

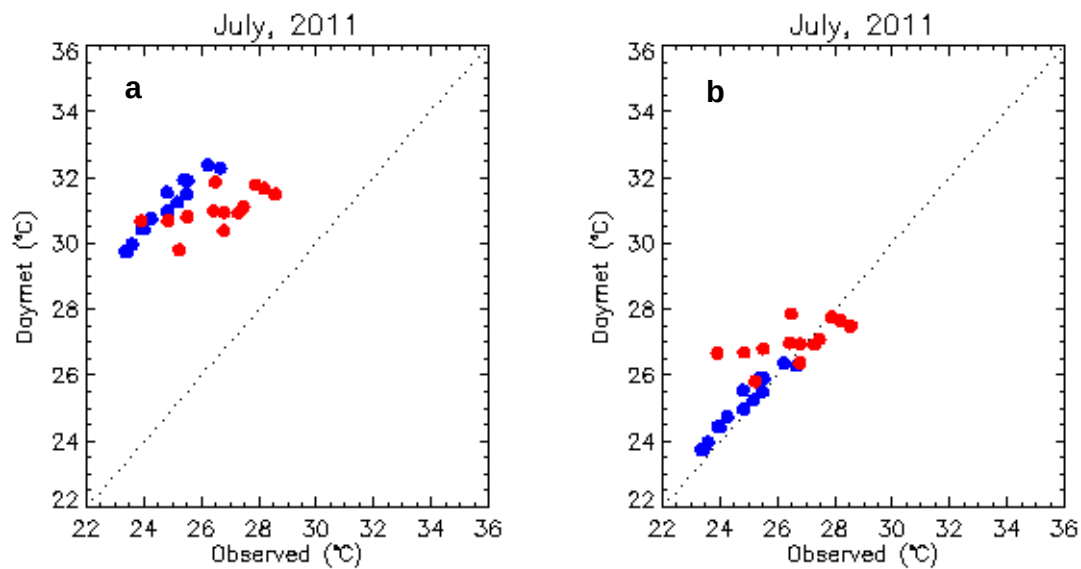


**Figure 19.** Comparison between observed temperature from HOBOS and downscaled temperatures from DAYMET for July 2011 for uncorrected DAYMET temperatures (a). Red dots indicate west slope, blue dots indicate east slope. MBE for west (east) slope is 4.27°C (6.24°C). Same for (b), but with the correction factor applied. With the correction factor, MBE for the west (east) slope is 0.27°C (0.24°C). Red dots indicate west slope, blue dots indicate east slope. Dotted line is 1:1 line. Only data from 2011 shown because DAYMET data from 2012 are not available as of June, 2013.

To remedy this discrepancy between the model and observations, we applied an empirical correction to the downscaled DAYMET data like we did when we statistically downscaled PRISM in Section 3.2.2. This correction factor is a function of season and on the side of the Blue Ridge and is needed to yield a more realistic approximation of the temperatures in these areas. In the case of mean July maximum temperatures, for sites located along the west side of the Blue Ridge 3.5°C and (4.0°C) should be subtracted for slopes with a southerly (non-southerly) orientation. For sites along the east side of the Blue Ridge, 5.5°C (6.0°C) should be subtracted for slopes with a southerly (non-southerly) orientation.

While we apply develop this approach to statistically downscale mean monthly maximum temperature using data from both PRISM and DAYMET, we do not do this for mean monthly

minimum temperature or relative humidity. Monthly minimum temperatures are affected by local terrain-induced processes such as drainage flows and cold air pooling (e.g. Daly et al., 2001), and thus the relationship between minimum temperature and elevation is not as straightforward as it is for mean monthly maximum temperature. Downscaling relative humidity is not presently possible using the downscaling approach presented here because high-resolution gridded data sets of atmospheric moisture variables are not available in PRISM at the same high resolution that temperature is available. Furthermore, relative humidity is affected by multiple near-surface processes and can exhibit large spatial variations that can occur independently of elevation.

### **3.2.3. WRF Evaluation**

We run the Weather Research and Forecasting model (WRF) for 3 nested domains, which is a common approach in atmospheric modeling to do weather simulations at high spatial resolution. The innermost domain with the highest spatial resolution has a 1 km horizontal resolution encompasses all of SNP (Figure 20). Ideally, the horizontal resolution of the atmospheric model would be equal to the one used for the statistical downscaling methods. However, the current state-of-the-art atmospheric modeling does not allow us to do so and a horizontal resolution of 1 km as the typical highest resolution in atmospheric modeling is widely accepted (e.g. Xie et al., 2013). Also note that a month-long simulation uses significant computational resources. A month-long simulation for the SNP takes about 72 hours in the 64-core computer cluster in the Department of Environmental Sciences at UVA.

Twenty-eight vertical levels are used between the land surface and the top of the troposphere. In our simulations, we set the model top to 100 mb. The mean heights of the lowest 10 vertical levels are approximately 30.5 m agl, 74.6 m agl, 132.0 m agl, 203.1 m agl, 292.5 m agl, 404.9 m agl, 535.9 m agl, 737.1 m agl, 934.6 m agl, and 1123.9 m agl. The highest concentration of vertical levels is near the surface so that the model can better resolve the atmospheric processes that are important to our investigations. We evaluate the model using Big Meadows observations for two months in two different seasons: January 2012 and July 2012 to investigate the model sensitivity to seasonal extremes.

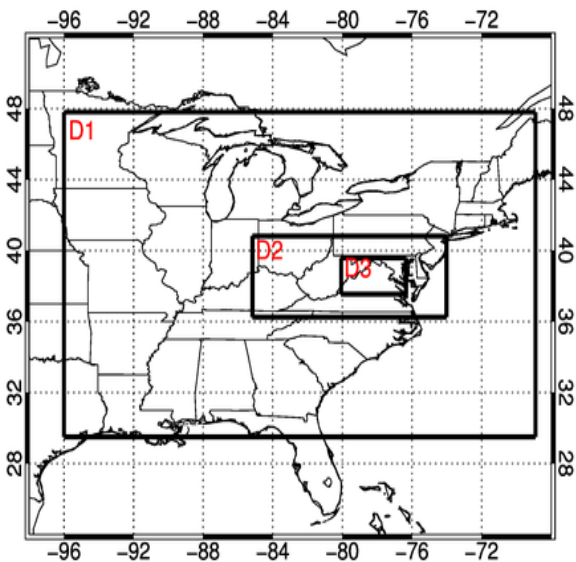


**Figure 20.** Map of three domains used in all WRF simulations using a latitude-longitude projection. The outermost domain (D1) has a spatial resolution of 9 km, the middle domain (D2) has a 3 km spatial resolution, and the innermost domain (D3) has a 1 km spatial resolution.

Atmospheric numerical models contain many ‘approximations’ which affect the uncertainty in surface temperature simulations. Of particular importance for surface temperature is the representation of the land surface and its interaction with the overlying atmosphere. The processes that are important for this representation are included in surface-layer and boundary layer parameterization schemes. By testing the sensitivity of the model output to the surface- and boundary layer parameterization schemes, we can obtain some indication of the uncertainty in the simulated temperature results. Sensitivity tests conducted during Year II of the project showed that temperatures were more sensitive to the land surface model (LSM) than to changes to the boundary layer parameterization scheme. Thus, in Year III of the project we evaluated the temperatures obtained by running WRF with two different LSMs: the Noah LSM which uses soil temperature and moisture in four layers (e.g. Chen and Dudhia, 2001), and the Pleim-Xiu LSM, which is a less computationally demanding two-layer scheme (Xiu and Pleim, 2001). Both LSMs characterize the dominant land cover type as mixed forest in SNP, though there are some patches of evergreen particularly above 1100 m msl.

Monthly time series of hourly temperature for July 2012 show good agreement between the observations at Big Meadows and output from WRF for the grid box containing Big Meadows (1058 m msl, which is 21 m below the actual elevation of Big Meadows) (Figure 21). However, the WRF configurations using these two different LSMs both tend to underestimate daytime maximum temperatures, sometimes by as much as 3°C (Table 9).

Quantifying moisture variability (i.e. both relative humidity and total monthly precipitation) is more difficult than quantifying temperature variability, and differences between the model simulations and

observations can at times be quite large, e.g. >10% in the case of relative humidity (Table 9). The mean bias error between mean daily relative humidity from the simulation using the Noah LSM (Pleim-Xiu LSM) and observations is 7.3% (4.6%), although there exists much variability around the mean (Figure 22). The larger errors in relative humidity compared with temperature likely arise because of errors in atmospheric moisture content and the temperature biases discussed previously.

In the case of accumulated monthly precipitation, both sensitivity tests show an overestimate. Total monthly precipitation using the Pleim-Xiu (Noah) LSM is about 2 times (2.5 times) larger than the observations. The difference is largely driven by one discrete, convective rainfall event during the middle of the month when the model simulations largely overestimated the rainfall that occurred. It is well-known that numerical weather prediction models such as WRF have difficulties simulating rainfall amounts (e.g. Jankov et al., 2005).

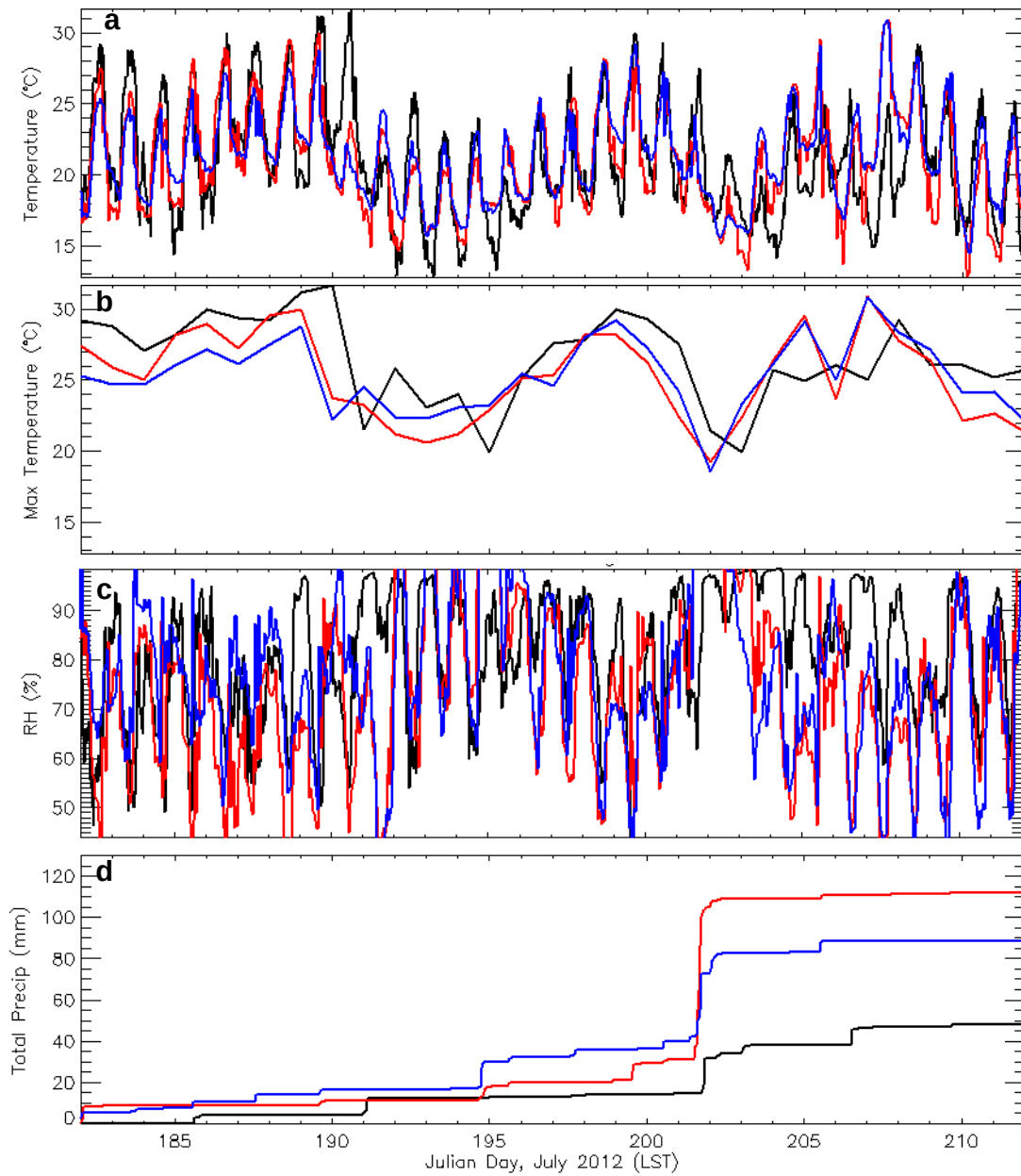


**Figure 21.** Evaluation of WRF for SNP for July 2012 by comparing observations from Big Meadows (black line) with model output using the Noah LSM (red line) and Pleim-Xiu LSM (blue line) for hourly temperature (a), mean daily maximum temperature (b), hourly relative humidity (c), and accumulated monthly precipitation (d) .

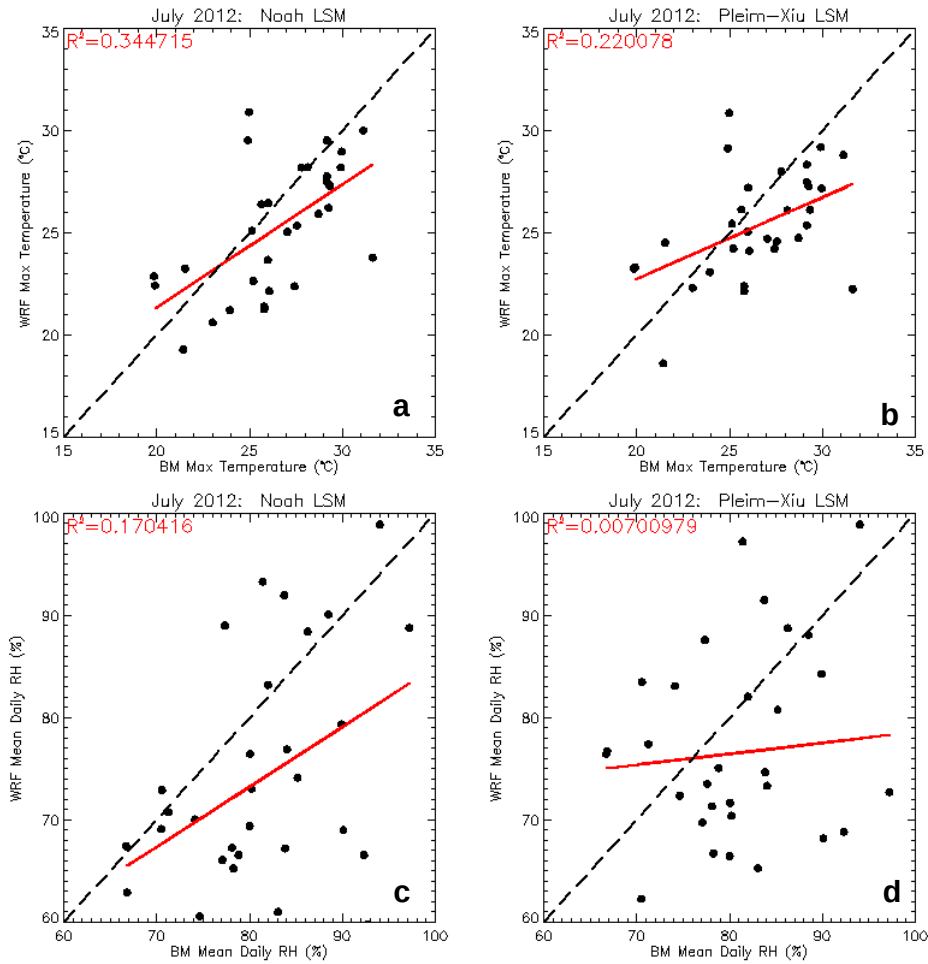


**Figure 22.** Daily mean maximum temperature from grid box containing Big Meadows as a function of the observed daily mean maximum temperature at Big Meadows for July, 2012 using the Noah LSM in WRF (a) and Pleim-Xiu LSM in WRF (b). Same for (c) and (d) but for mean daily relative humidity.  $R^2$  and line of best fit shown in red. Dashed line is 1:1 line.

**Table 9.** Root mean square error (RMSE) and mean bias error (MBE) for sensitivity tests for July, 2012 daily mean maximum temperature and daily mean relative humidity.

|               | July, 2012<br>Daily Maximum Temperature |          | July, 2012<br>Daily Mean Relative Humidity |         |
|---------------|-----------------------------------------|----------|--------------------------------------------|---------|
|               | RMSE (°C)                               | MBE (°C) | RMSE (%)                                   | MBE (%) |
| Noah LSM      | 3.07                                    | -1.24    | 12.78                                      | 7.26    |
| Pleim-Xiu LSM | 3.15                                    | -1.16    | 12.86                                      | 4.63    |

We perform the same sensitivity tests for January, 2012. Consistent with our findings from PRISM and DAYMET, WRF does a better job representing temperatures in January than during July (Figure 23). Monthly maximum temperature is slightly underestimated by the model, but both relative humidity and accumulated monthly precipitation agree much better with the observations (Figure 24, Table 10) than the July, 2012 simulations.

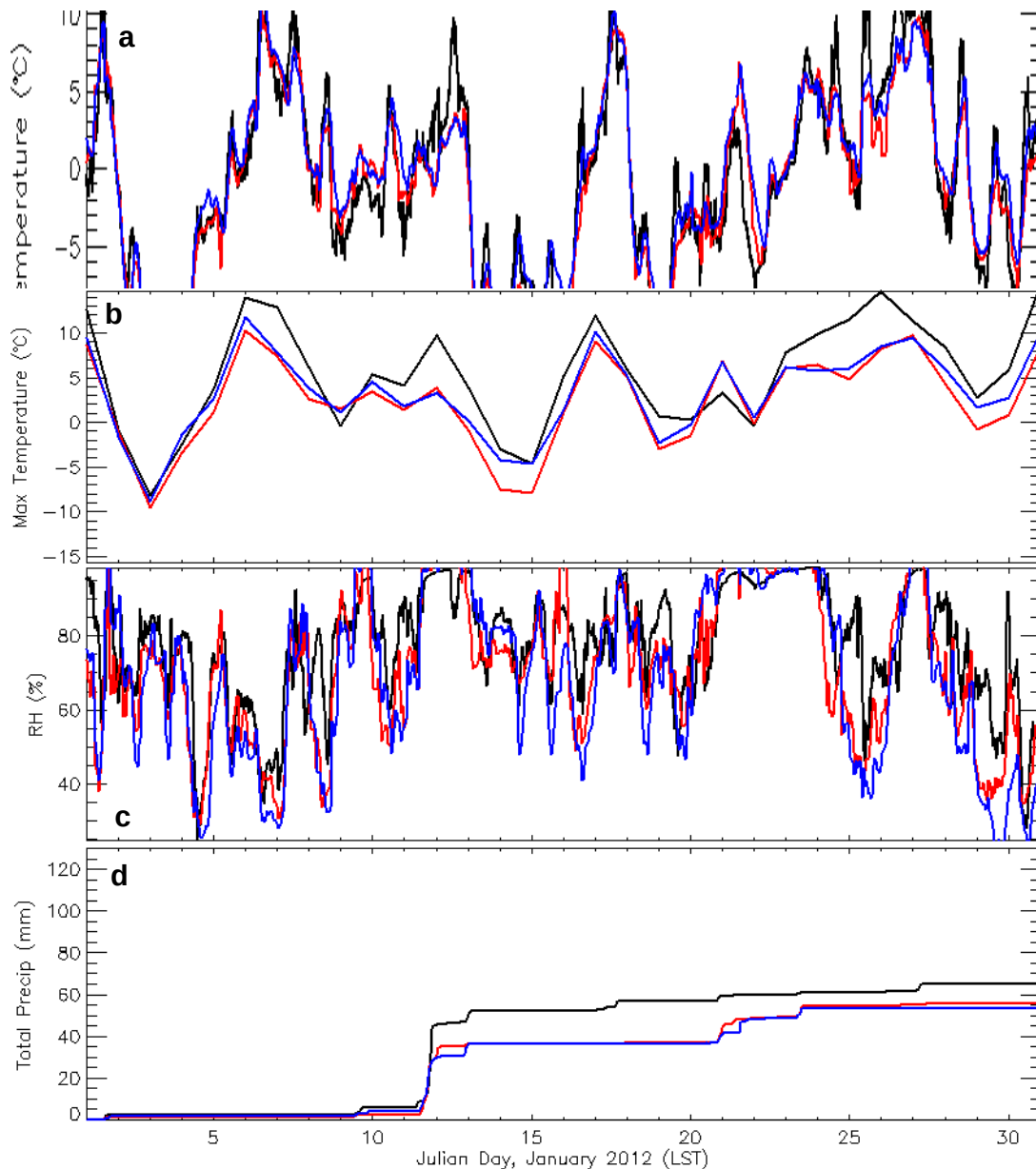


**Figure 23.** Evaluation of WRF for SNP for January 2012 by comparing observations from Big Meadows (black line) with model output using the Noah LSM (red line) and Pleim-Xiu LSM (blue line) for hourly temperature (a), mean daily maximum temperature (b), hourly relative humidity (c), and accumulated monthly precipitation (d).

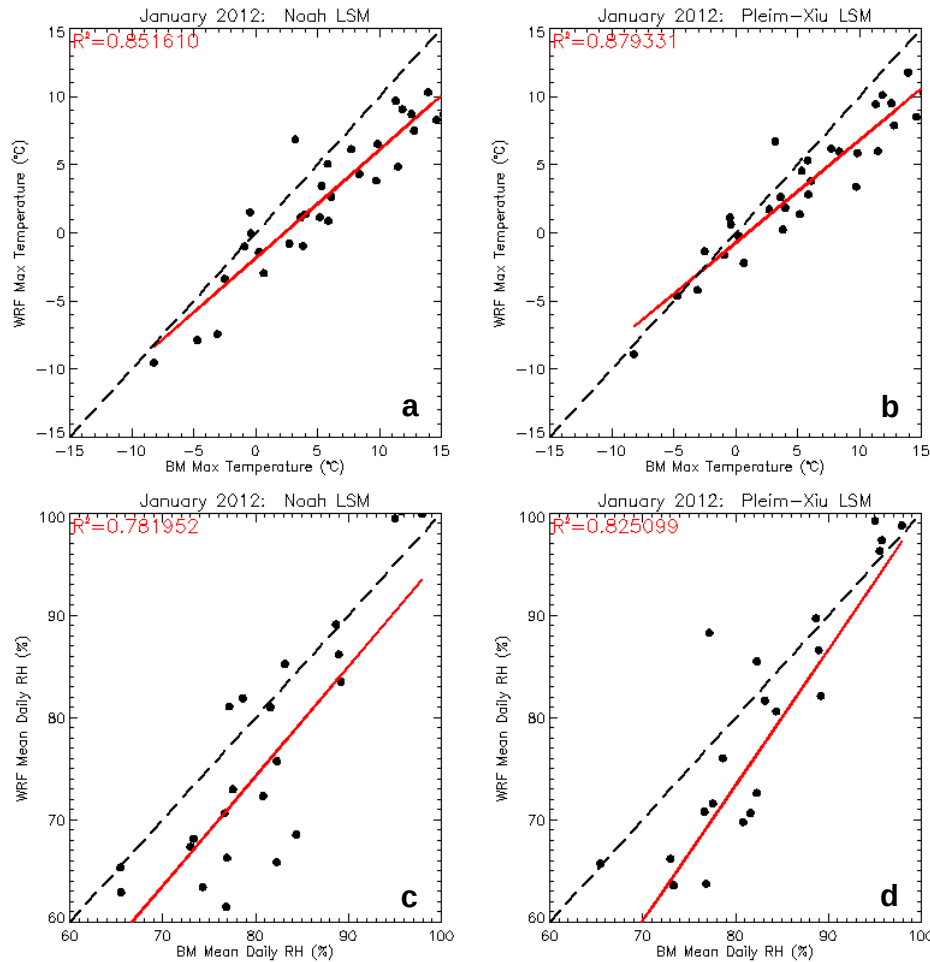


**Figure 24.** Daily mean maximum temperature from grid box containing Big Meadows as a function of the observed daily mean maximum temperature at Big Meadows for January, 2012 using the Noah LSM in WRF (a) and Pleim-Xiu LSM in WRF (b). Same for bottom (c) and (d) but for mean daily relative humidity.  $R^2$  and line of best fit shown in red. Dashed line is 1:1 line.

|                      | January, 2012<br>Daily Maximum Temperature |          | January, 2012<br>Daily Mean RH |          |
|----------------------|--------------------------------------------|----------|--------------------------------|----------|
|                      | RMSE (°C)                                  | MBE (°C) | RMSE (%)                       | RMSE (%) |
| <b>Noah LSM</b>      | 3.78                                       | -2.96    | 9.55                           | 9.55     |
| <b>Pleim-Xiu LSM</b> | 3.05                                       | -2.06    | 12.16                          | 12.16    |

**Table 10.** RMSE and MBE for sensitivity tests for January, 2012 daily mean maximum temperature and daily mean relative humidity.

We further evaluate the WRF model output using data from the HOB0 network, focusing now exclusively on the sensitivity to mean monthly maximum temperature during the summer months. We find that mean monthly maximum temperature is overestimated at most of the HOB0 locations with negligible differences in monthly mean maximum temperature with the two LSMs (Figure 25). The MBE between the observations (i.e. mean monthly maximum temperatures from the slope locations, and from Pinnacles and Big Meadows) and WRF model simulations using the Noah LSM is 1.18°C and 1.34°C using the Pleim-Xiu LSM (note that positive MBE indicates the model is higher than the observations). Correcting for elevation differences between the model and observations using a mean July lapse rate (which we obtain from PRISM) of 7°C km<sup>-1</sup>, we find that the MBE improves to 1.15°C and 1.28°C for the WRF simulation run using the Noah LSM and the WRF simulation run using the Pleim-Xiu LSM, respectively.

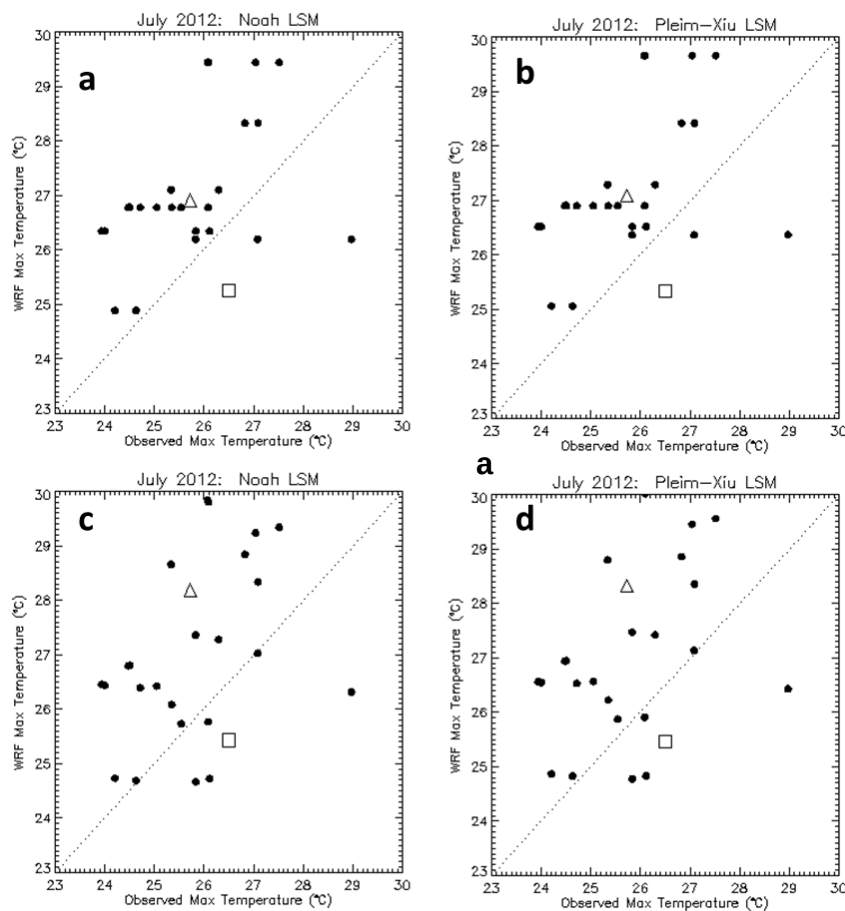


**Figure 25.** Mean monthly maximum temperature as a function of observations from HOB0s (filled circles), Pinnacles (open triangle), and Big Meadows (open square) using the Noah LSM (a) and Pleim-Xiu LSM (b). Same for (c) and (d) but correcting for elevation differences between the elevation of the WRF grid box and the elevation of the HOB0. Dotted line is 1:1 line.

### 3.3. Maps of present-day spatial temperature variability

One common feature of both the statistical downscaling methods (using PRISM and DAYMET) and dynamical downscaling methods (using WRF) is that both methods tend to overestimate temperatures, particularly along the slopes. These biases are typically largest during the summer and along the eastern side of the Blue Ridge. In the case of PRISM and DAYMET, we found that these biases could be as large as 4°C and 6°C, respectively, in the month of July along the east slope. However, the biases were smaller for output from the WRF model than for the PRISM/ DAYMET data sets. Despite this slightly better agreement, one main advantage of using high-resolution gridded climate data sets instead of running WRF is that the high-resolution gridded data sets are readily available online at resolutions of 1-4 km. Comparatively, generating output from WRF at the spatial scales needed for this study (< 1 km) by running the model itself is not straightforward and is computationally expensive (see Section 3.2.3) and thus running WRF for time periods of >1 month for multiple years is very computationally demanding.

In order for gridded climate data sets such as PRISM and DAYMET to be used reliably both in estimates of current temperature and in projections of future temperature changes, they need to be downscaled further, and an empirical correction factor must be applied to the downscaled temperature estimates (Figure 26). Applying a variable, grid-specific lapse rate correction discussed earlier, we get a more accurate depiction of near-surface temperatures.

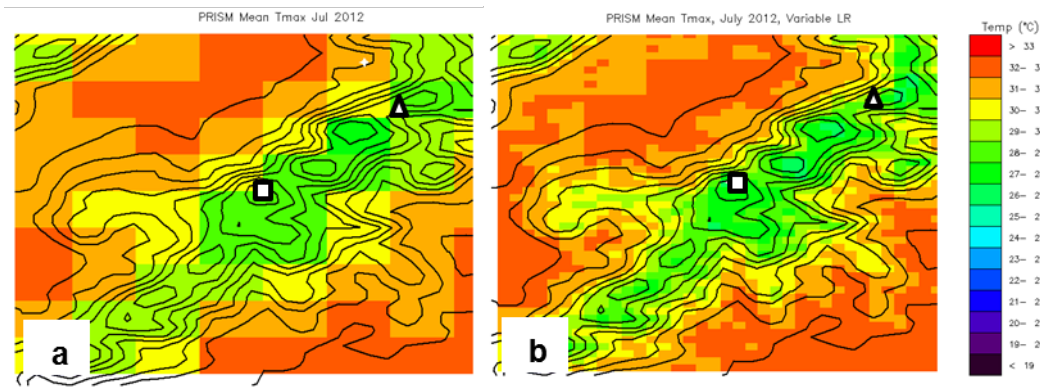


**Figure 26.** 4 km PRISM temperatures for July 2012 (a) and downscaled using a monthly-varying lapse rate based on 30-year climate normals (b). White triangle and white square show locations of Pinnacles and Big Meadows, respectively. Note that the pixels are not square because we converted the data from a latitude-longitude projection, which uses degrees, into the Universal Transverse Mercator (UTM) projection, which use meters.

Consistent with what is shown earlier, there are only small differences in mean July maximum temperature for the two different LSMs that we evaluated in WRF. The Noah LSM provides slightly

better estimates of mean monthly maximum temperature in the region, as the MBE is lower than for the Pleim-Xiu LSM, but maps of temperature from both are shown are quite similar (Figure 27).

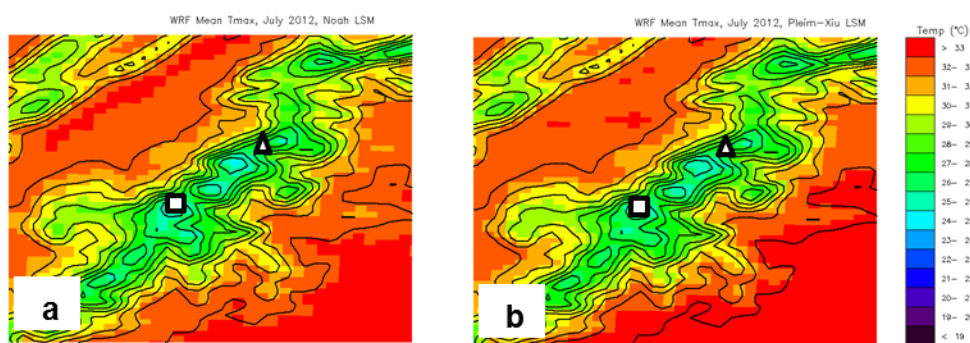


**Figure 27.** Mean monthly maximum temperature for July 2012 from WRF using the Noah LSM (a) and Pleim-Xiu LSM (b). White triangle and white square show locations of Pinnacles and Big Meadows, respectively.

As has been previously stated, relative humidity shows poorer agreement between model and observations and is much more variable spatially. To highlight these differences, we show maps of the mean monthly relative humidity and total monthly precipitation from the two different LSMs that we used in WRF (Figure 28). The WRF simulation using the Noah LSM generally shows lower mean monthly relative humidity than the Pleim-Xiu LSM, yet slightly greater total rainfall in the domain encompassing SNP than the WRF simulation that used the Pleim-Xiu LSM.

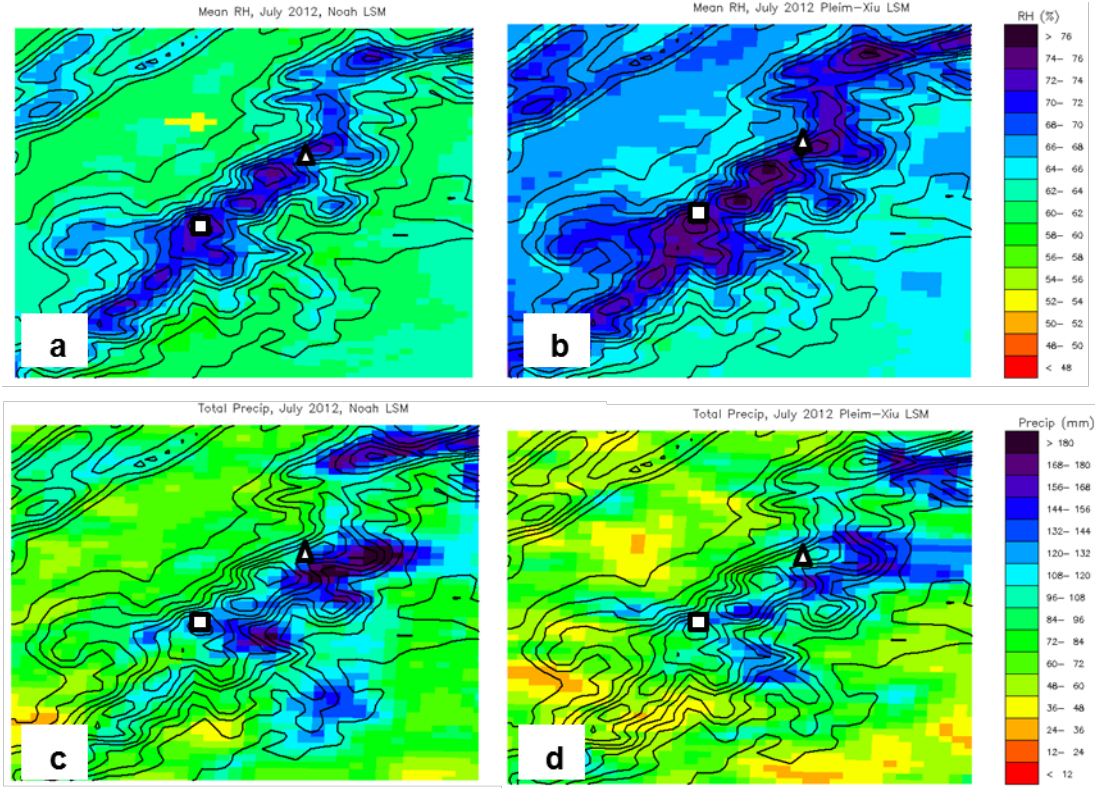


**Figure 28.** Mean daily relative humidity for July 2012 from WRF using the Noah LSM (a) and Pleim-Xiu LSM (b). Same for (c) and (d) but for total monthly precipitation. White triangle and white square show locations of Pinnacles and Big Meadows, respectively.

However, as discussed in previous sections, the downscaled results from PRISM do not compare well with temperature observations, even when we account for differences in lapse rate. For this reason, we applied two additional corrections to these results which we derived in Section 3.2, are shown in Table 6 and are summarized below:

1. We found that the downscaled PRISM results agreed better with observations along the west side of the Blue Ridge than along the east side of the Blue Ridge. For this reason, we applied a correction factor that was a function of a point's location relative to the ridgeline of the Blue Ridge. To account for the discrepancies between the model results and observations, we used an empirical correction factor of  $2^{\circ}\text{C}$  when downscaling to a 15 m DEM, which was subtracted from the downscaled PRISM results to better account for present-day mean monthly maximum temperatures in July. The agreement between the model results and observations was worse along the east side of the Blue Ridge. For points east of the ridgeline of the Blue Ridge, we imposed a correction factor of  $4^{\circ}\text{C}$ . As these correction factors vary in different months, with larger correction factors in the summer when the effects of canopy cover on temperature are largest, the effects of canopy cover on the near-surface temperature measurements are incorporated into the correction factors.

2. We also found temperature differences as a function of slope azimuth. Temperatures along the south-facing slopes of the Cedar Run Trail were about  $0.5^{\circ}\text{C}$  warmer than those along the east/northeast facing slopes. To account for this difference, we added an offset of  $0.5^{\circ}\text{C}$  to slopes with a southward orientation (i.e. between  $135^{\circ}$  and  $225^{\circ}$ ), regardless of the location of the site along the east side or west side of SNP.

With the use of these additional correction factors, we were better able to describe present-day near-surface temperatures in SNP. The use of these correction factors is reflected in Figure 29.

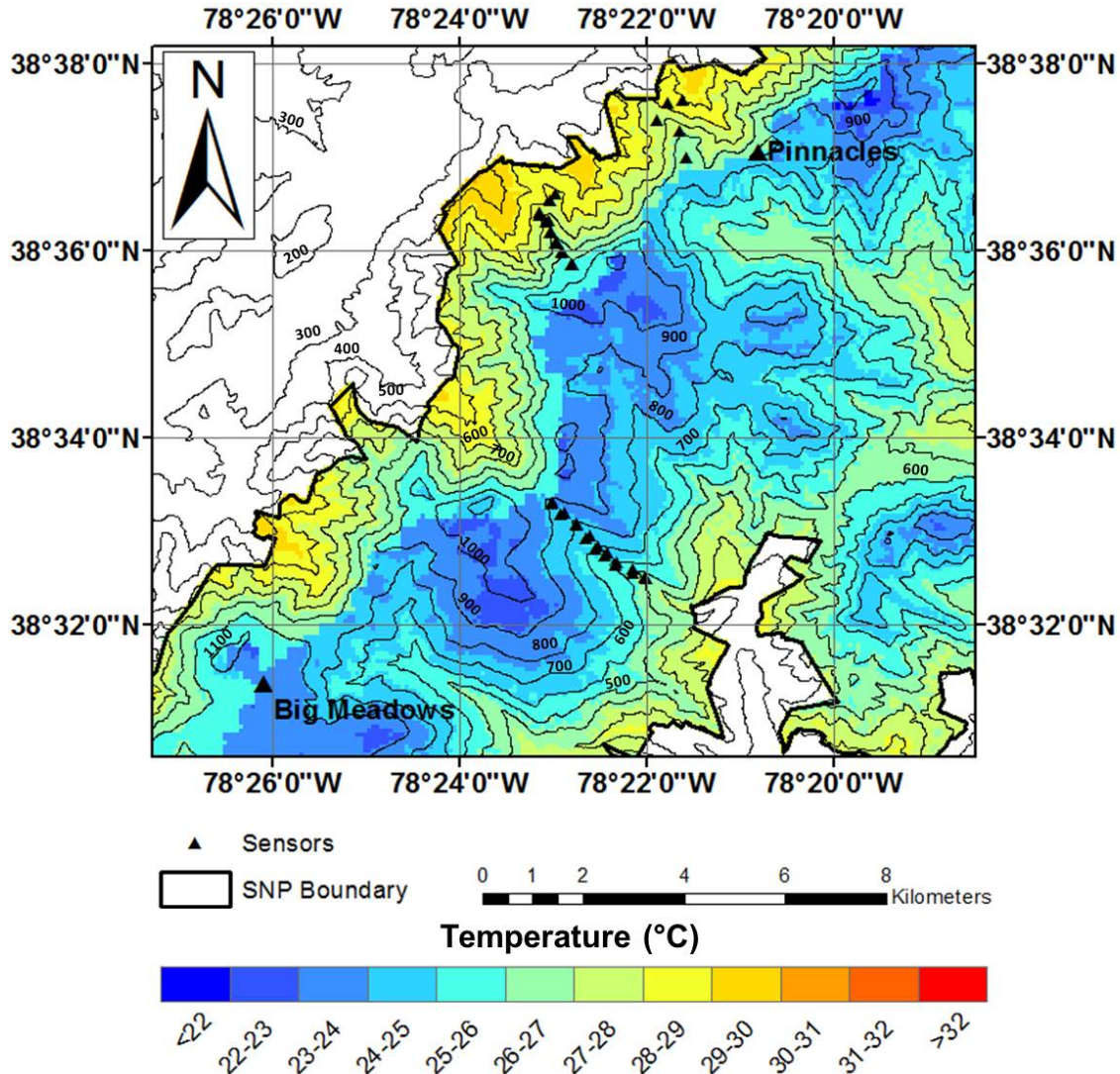


**Figure 29.** 15 m spatial resolution map of mean July maximum temperature in SNP. July, 2012 is shown as an example. Elevation contours in black every 100 m; black line denotes SNP boundary; black triangles mark temperature sensors; and the two ridgetop climate monitoring stations, Big Meadows and Pinnacles, are labeled.

### 3.4. Climate Models

In this section, we create maps of present-day and future climate projections of temperature variations within SNP using output from RCMs for the region.

#### 3.4.1. *Relationship between Big Meadows and Regional Climate Models*

We compared output from seven of the NARCCAP RCMs, which have a 50 km spatial resolution (Mearns et al., 2009; Mearns et al., 2012), with mean July maximum and minimum temperature from Big Meadows for the period 1971-2000. Due to the coarse resolution of the NARCCAP RCMs, the elevation of the grid box containing Big Meadows is 283 m msl, whereas the actual elevation of Big Meadows is 1079 m msl. In this comparison, we do not correct for elevation differences, and thus the model overestimates temperatures at Big Meadows by  $\sim 5^{\circ}\text{C}$  (Figure 30). Temperature differences among the suite of NARCCAP RCMs arise because the RCMs are driven by different GCMs.

However, the interannual variability in both maximum temperature and minimum temperature at Big Meadows is not captured well by any of the seven RCMs. For example, the Big Meadows observations of mean maximum temperature between 1995 and 1998 show a decreasing trend that is consistent with findings at outer mountaintops in the southeast US, e.g. Mount Mitchell, North Carolina (Saxena and Menon, 1999), as well as temperature trends at other sites in the Southeast US (e.g. Rogers, 2013). However, the suite of NARCCAP RCMs suggests a temperature increase during this period. This discrepancy highlights some of the rather large differences that have been found to occur when comparing mountaintop observations with output from RCMs (e.g. New et al., 1999) and may suggest an inaccuracy in the performance of the RCMs in this particular region. Determining exactly why this discrepancy occurs between the NARCCAP RCMs and the observations at Big Meadows requires further investigations that are beyond the scope of the present investigation.

Despite limitations capturing the interannual temperature variability, the NARCCAP RCMs capture temperature trends on the decadal scale and show an upward trend in mean annual temperatures at Big Meadows beginning in 1980 that is consistent with observations. Since we are interested in temperature changes on decadal rather than yearly timescales and because the NARCCAP RCMs have been recently used in many other studies to develop temperature change projections (e.g. Bukovsky, 2012; Elguindi and Grundstein, 2013; He et al., 2014), we are confident in using NARCCAP RCMs to help develop future temperature projections for SNP.

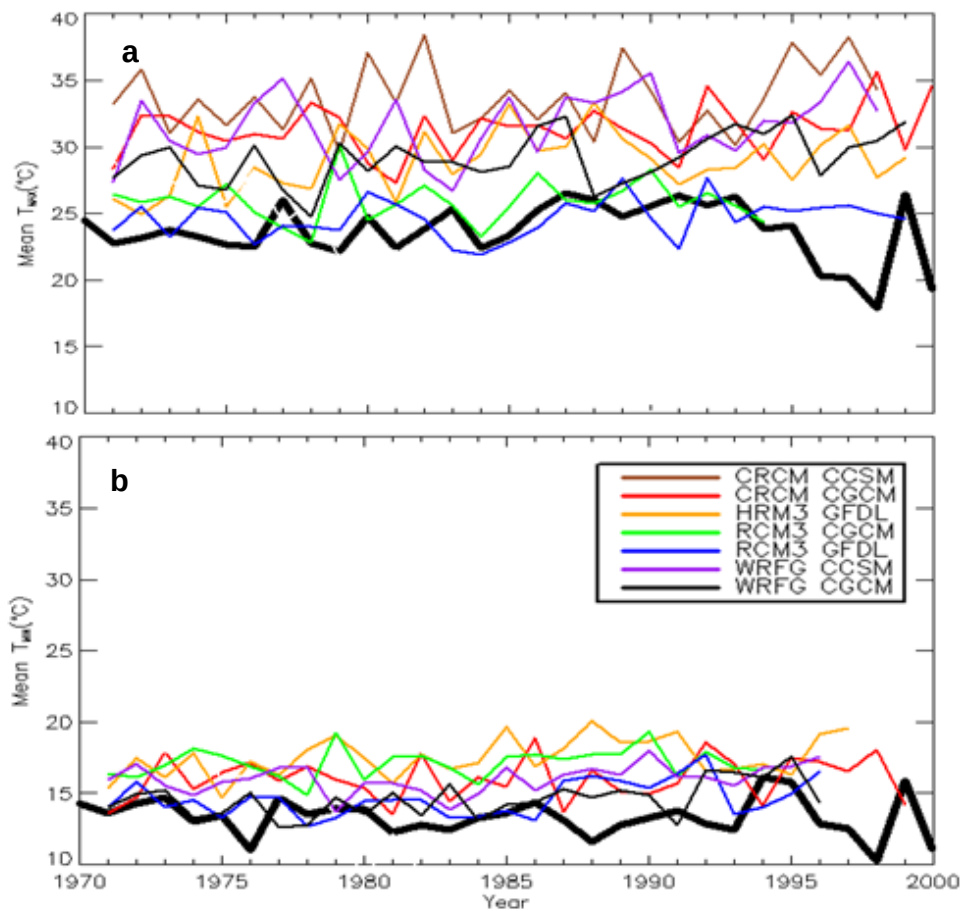


**Figure 30.** Comparison between mean July maximum temperature observed at Big Meadows and a suite of NARCCAP RCMs, 1970-2000 (a). Thick black line represents Big Meadows observations; CRCM-CCSM: brown; CRCM-CGCM: red; HRM3-GFDL: orange; RCM3-CGCM: green; RCM3-GFDL: blue; WRFG-CCSM: purple; WRFG-CGCM: black. Same for (b) but for mean July minimum temperature. Note that output from several RCMs is not available past 1996.

### 3.4.2. Climate change projections for SNP using RCMs

We use the RCMs to project future climate change in the Mid-Atlantic to illustrate some of the uncertainty in climate change projections for the region. Whereas our focus in this study is on changes in maximum temperatures, we also show projected changes in minimum temperature and precipitation for completeness.

To determine the rate of change in temperature and precipitation in amount per decade, we determine the mean value for the grid box containing Big Meadows over the period 1971-2000 and for 2041-

2070, which represents a 70 year difference. We simply divide this result by 7 to obtain the average change per decade.

NARCCAP RCMs project that maximum July temperatures may increase by  $0.3\text{--}0.6^{\circ}\text{C decade}^{-1}$ , which represents about a  $2\text{--}4^{\circ}\text{C}$  increase through the year 2055 (Figure 31). For the grid box containing Big Meadows, the GFDL-HRM3 model shows the largest temperature increase per decade ( $+0.60^{\circ}\text{C decade}^{-1}$ ), whereas the CGCM-WRFG model projects the smallest increase ( $0.29^{\circ}\text{C decade}^{-1}$ ) (Table 11). Similar projections are found for changes in mean July minimum temperature (Figure 32), although the magnitude of the change is about  $0.05^{\circ}\text{C decade}^{-1}$  smaller than the projections for the increase in maximum temperature. We note, however, that the projected increases in temperature may be nonlinear and might show a possible acceleration of warming near mid-century.

Whereas temperatures are expected to increase in SNP and throughout the Mid-Atlantic, changes in precipitation are less clear. 4 of the 7 NARCCAP RCMs suggest that total July precipitation will increase at Big Meadows, whereas the other 3 suggest a decrease. These differences are seen in other parts of the Mid-Atlantic (Figure 33) and underscore the difficulties associated with obtaining reliable precipitation projections. Since precipitation amounts affect the moisture content of the atmosphere, reliable projections of relative humidity are also difficult to make.

**Table 11.** Projected change in mean July maximum temperature, July minimum temperature, and total July precipitation averaged over 2041-2070, compared to 1971-2000 averages, for the grid box containing Big Meadows. Shown in parentheses is the projected change in  $^{\circ}\text{C decade}^{-1}$ .

| GCM-RCM                                     | $\Delta T \text{ max } (^{\circ}\text{C})$                      | $\Delta T \text{ min } (^{\circ}\text{C})$                      | $\Delta \text{ Precipitation (cm)}$                               |
|---------------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|-------------------------------------------------------------------|
| CCSM-CRCM                                   | +3.37 (+0.48)                                                   | +2.90 (+0.41)                                                   | +0.17 (+0.02)                                                     |
| CGCM-CRCM                                   | +3.91 (+0.56)                                                   | +3.57 (+0.51)                                                   | +0.30 (+0.04)                                                     |
| CCSM-WRFG                                   | +3.44 (+0.49)                                                   | +2.47 (+0.35)                                                   | -0.55 (-0.08)                                                     |
| CGCM-WRFG                                   | +2.04 (+0.29)                                                   | +2.12 (+0.30)                                                   | +0.16 (+0.02)                                                     |
| GFDL-HRM3                                   | +4.23 (+0.60)                                                   | +3.83 (+0.55)                                                   | -0.0076 (0.00)                                                    |
| CGCM-RCM3                                   | +2.74 (+0.39)                                                   | +2.49 (+0.36)                                                   | -0.71 (-0.10)                                                     |
| GFDL-RCM3                                   | +3.11 (+0.44)                                                   | +2.76 (+0.39)                                                   | -0.087 (-0.01)                                                    |
| <b>MEAN <math>\Delta \pm 1\sigma</math></b> | <b>+3.26<math>\pm</math>0.73<br/>(0.47<math>\pm</math>0.10)</b> | <b>+2.87<math>\pm</math>0.62<br/>(0.41<math>\pm</math>0.09)</b> | <b>-0.10<math>\pm</math>0.38<br/>(-0.014<math>\pm</math>0.05)</b> |

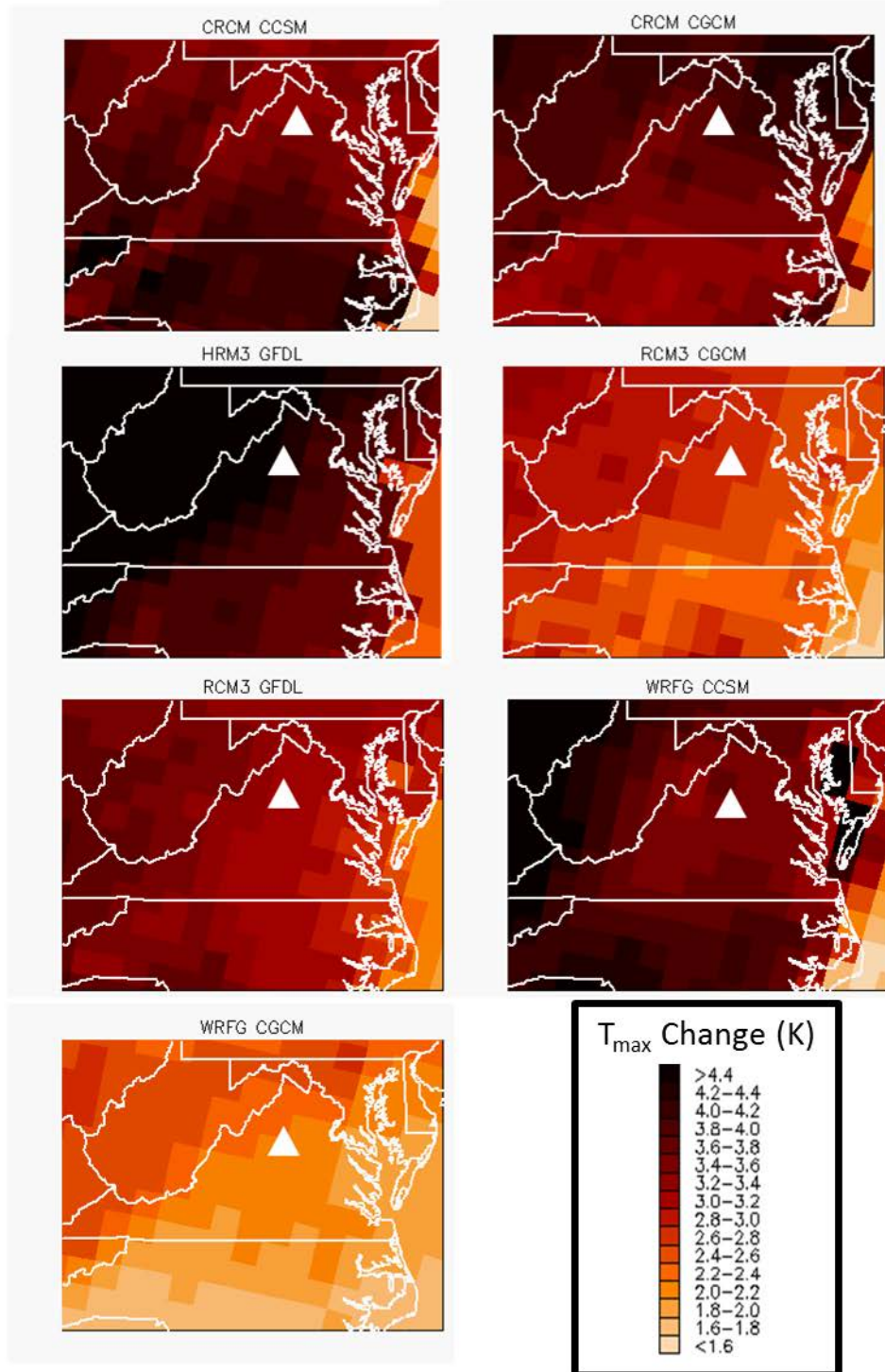


**Figure 31.** Projected change in mean July maximum temperature ( $^{\circ}\text{C}$ ), averaged over 2041-2070, compared to mean July maximum temperature averaged over 1971-2000 for 7 different NARCCAP GCM-RCM combinations (the parent GCM and RCM are listed at the top of each panel). Location of Big Meadows is shown with a white triangle.

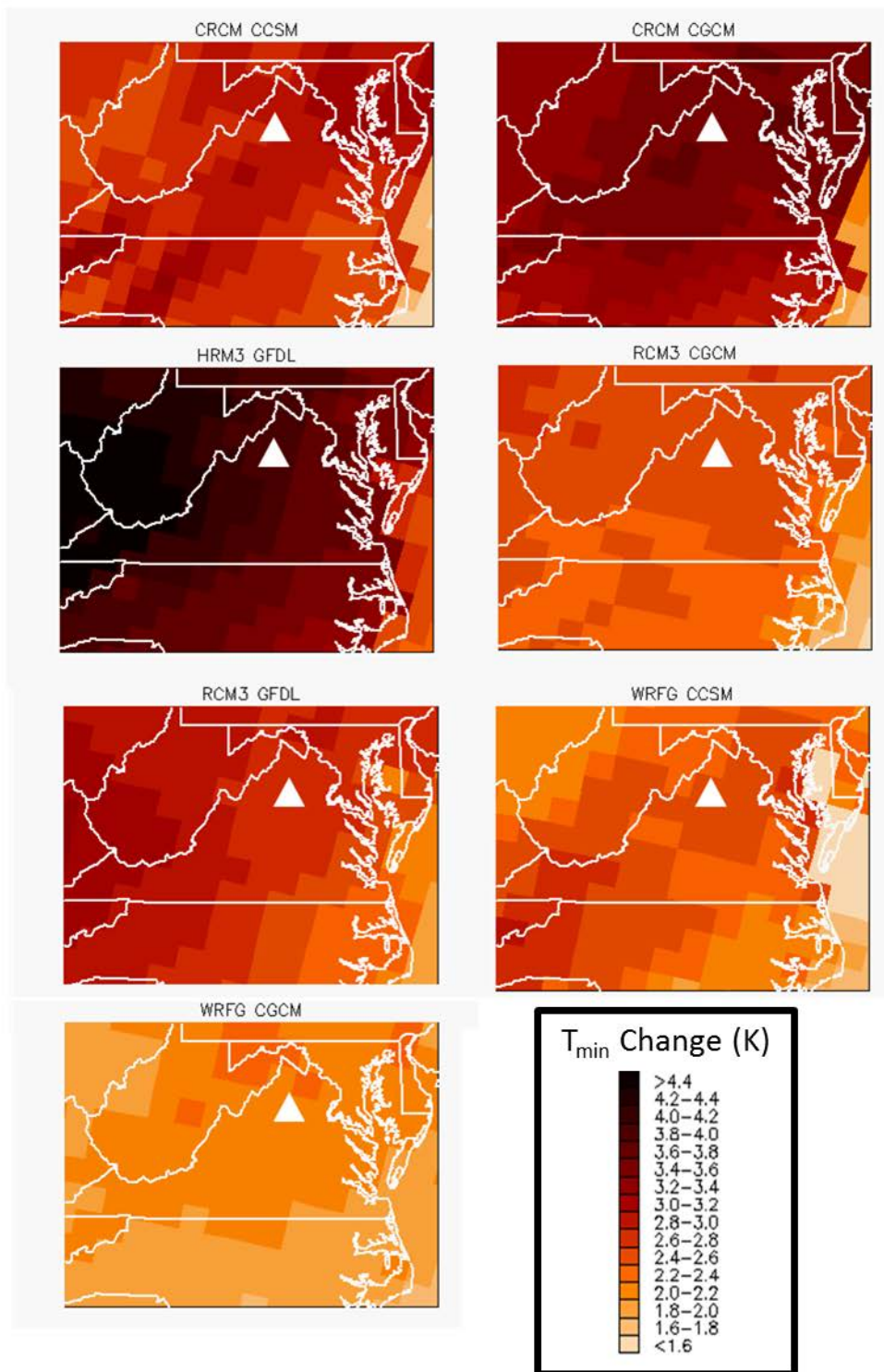


**Figure 32.** Projected change in mean July minimum temperature ( $^{\circ}\text{C}$ ), averaged over 2041-2070, compared to mean July minimum temperature averaged over 1971-2000 for a suite of 7 NARCCAP RCMs (the parent GCM and RCM are listed at the top of each panel). Location of Big Meadows is shown with a white triangle.

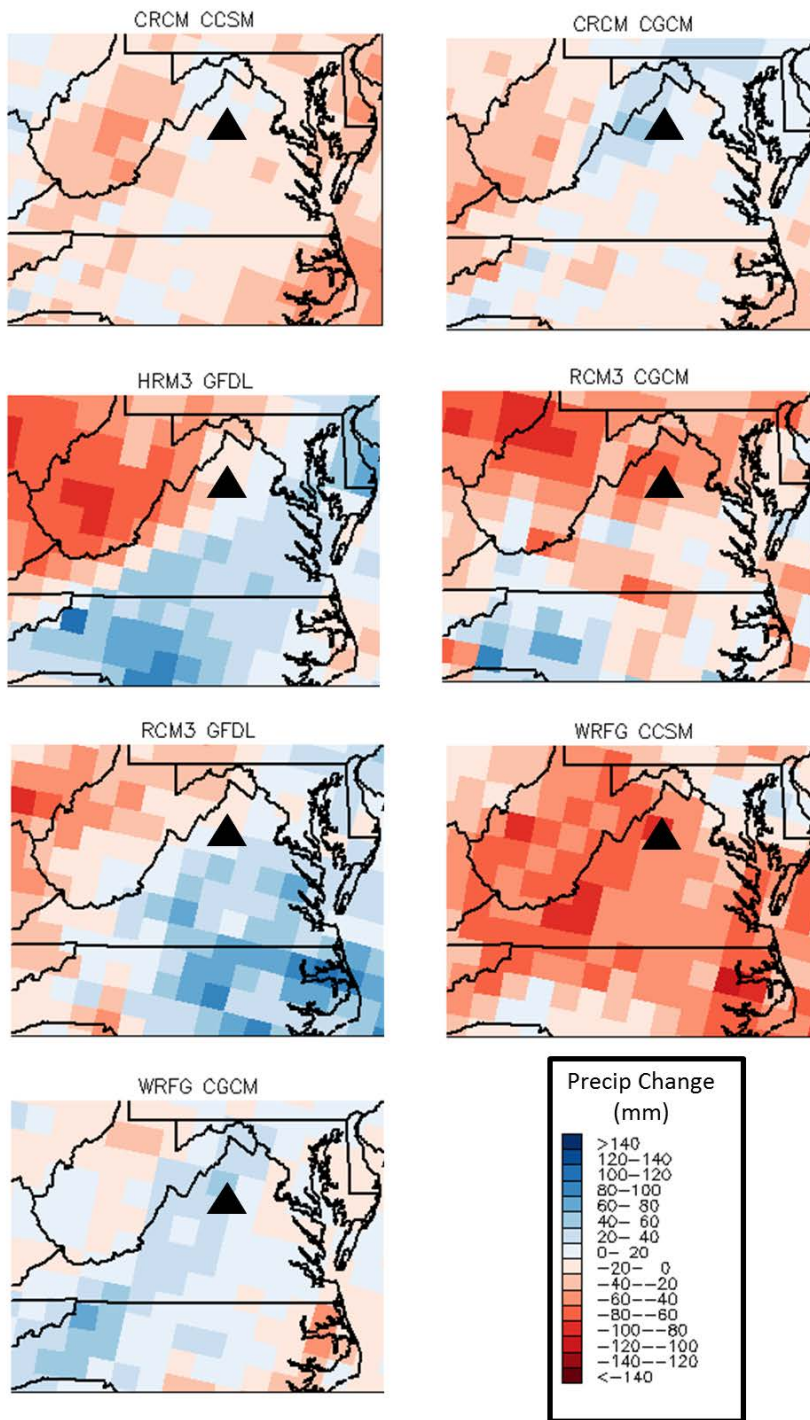


**Figure 33.** Projected change in mean July precipitation (mm), averaged over 2041-2070, compared to mean July precipitation averaged over 1971-2000 for a suite of 7 NARCCAP RCMs (the parent GCM and RCM are listed at the top of each panel). Location of Big Meadows is shown with a black triangle.

NARCCAP projections only assume one emissions scenario and cannot provide an indication of the uncertainty in climate projections due to uncertainty in future emission scenarios. Therefore, we also use output from other RCMs. In particular, we use output from the ICTP Regional Climate Model Version 3 (RegCM3) [see <http://users.ictp.it/~pubregcm/> for more information] to understand the variation in projected temperature changes for SNP. Projections from different emissions scenarios are presently available for the years 2055-2064 and for the years 2090-2099. Under the committed climate change scenario (which assumes that atmospheric CO<sub>2</sub> concentrations remain constant at their levels from 2000), mean annual temperatures decrease at Big Meadows (Table 12) and throughout the Mid-Atlantic (Figure 34). However, the latter two scenarios (i.e. the Special Report on Emissions Scenario [SRES] B1 and A1F1 scenarios which assume higher emissions compared with the committed climate change scenario, which assumes Year 2000 greenhouse gas concentrations, i.e. ~370 ppm [IPCC, 2007]) both suggest temperature increases of >4°C over present-day values at Big Meadows, which is consistent with other parts of the Mid-Atlantic. Under the A1FI and B1 scenarios, temperatures are projected to increase by ~7°C and ~3.4°C, respectively, in the late 20<sup>th</sup> century.

The ICTP RegCM3 models, which use the A1FI scenario in one simulation and the B1 scenario in another simulation, project greater increases in temperature for Big Meadows than the NARCCAP RCMs, which use the A1B emissions scenario. Both scenarios suggest temperatures may increase at an average rate of 0.62 and 0.65°C per decade through ~2060, whereas all NARCCAP RCMs project temperatures will increase <0.6°C per decade.

**Table 12.** Projected mean annual temperature change averaged over the years 2055-2064 and 2090-2099, compared to 1990-1999 averages for the grid box containing Big Meadows. Note that no climate change projections for the committed climate change scenario are available for 2090-2099. Shown in parentheses is the projected temperature change in °C decade<sup>-1</sup>.

|                                 | 2055-2064 $\Delta T$ (°C) | 2090-2099 $\Delta T$ (°C) |
|---------------------------------|---------------------------|---------------------------|
| <b>Committed Climate Change</b> | -3.31 (-0.51)             | -----                     |
| <b>SRES B1</b>                  | +4.06 (+0.62)             | +3.38 (0.34)              |
| <b>SRES A1FI</b>                | +4.24 (+0.65)             | +6.99 (0.69)              |

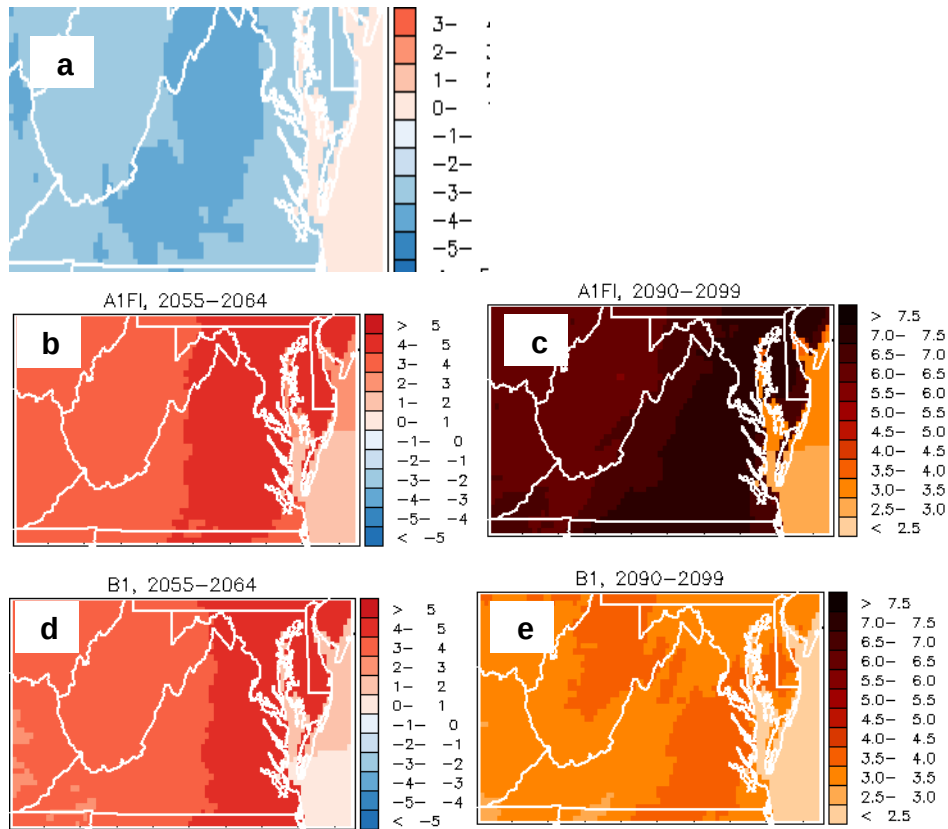


**Figure 34.** Projected increase in mean annual temperatures (°C) from the ICTP RegCM3 model, averaged over 2055-2064 (left column) and compared to 1990-1999 under the committed climate change scenario (a), A1F1 climate change scenario (b), and B1 climate change scenario (d). Panels in the right column show the increase in mean annual temperatures (°C), averaged over 2090-2099 and compared to 1990-1999 for the A1F1 climate change scenario (c) and B1 climate change scenario (e). Note that no committed climate change output is available for the period 2090-2099.

### 3.5. Downscaled climate change projections for SNP

The final step of this project was to downscale the RCM projections to 15 m in SNP. Using the statistical and dynamical downscaling methods, we downscale climate model output to SNP based on the RCM projections. NARCCAP RCMs project that mean July maximum temperatures in the year 2055 (i.e. the median of all years 2041-2070) will be 3.3°C higher in the grid box containing Big Meadows than present day values based upon averaging output from seven NARCCAP RCMs. (see Table 8). We can apply the projected temperature increase obtained from the NARCCAP RCMs to the maps of present-day mean July maximum temperature to get projected future temperature patterns in SNP (Figure 35).

Important to note, though, is that the projected temperature increase of  $3.3^{\circ}\text{C}$  between 1985 and 2055 is simply an average of all NARCCAP RCMs which assume one emissions scenario (i.e. A1B, which is a moderate emissions scenario that makes the assumption that energy is generated from a balanced use of fossil fuels and non-fossil fuels [IPCC, 2007]). To understand projected temperature increases in SNP under different emissions scenarios, we use output from the RegCM3. Of the three emissions scenarios used in the RegCM3, the SRES A1FI is the most pessimistic and projects temperature increases in the Mid-Atlantic region over present-day values of  $7.0^{\circ}\text{C}$  between 1990-1999 and 2090-2099. Using our downscaling methods, we apply this increase to the region to obtain high-resolution temperature projections under the most pessimistic emissions scenarios.

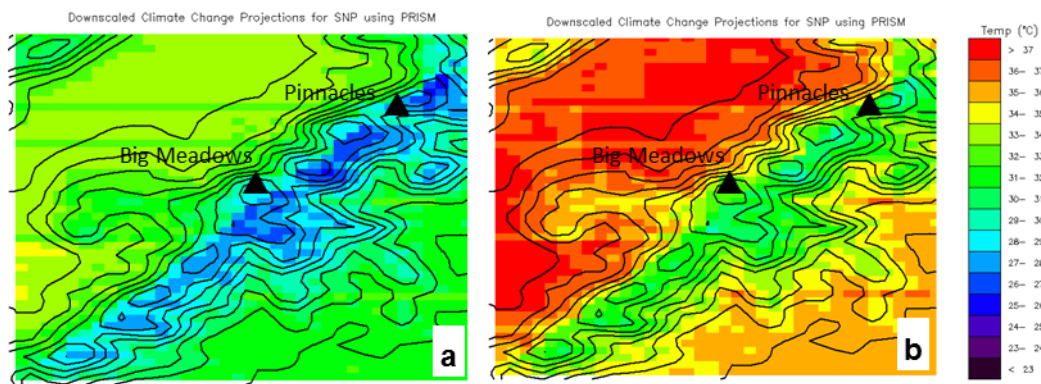


**Figure 35.** Projected mean July maximum temperatures for the period 2041-2070 applying a temperature increase of  $3.3^{\circ}\text{C}$  (average projected temperature increase from NARCCAP RCMs for Big Meadows) to mean July maximum temperatures obtained from PRISM (a). Same for (b), but assuming a temperature increase of  $7.0^{\circ}\text{C}$  (projected temperature at Big Meadows from the RegCM3 RCM using the SRES A1FI emissions scenario). Labeled black triangles indicates Pinnacles and Big Meadows.

These climate change projections can be downscaled further using the correction factors in Table 8 from Section 3.2.1. We apply a different correction factor depending on if a site is located to the west or to the east of the crest of the Blue Ridge and if a site has a southward orientation resulting in maps of the projected increase in mean July maximum temperatures in SNP. Using this approach, we construct climate change estimates for mean July maximum temperatures at a 15 m resolution for the NARCCAP emissions scenario. Because there is a range in the NARCCAP projections depending on the GCM-RCM combination used, to show the uncertainty in the temperature projections within the suite of NARCCAP models, we construct maps for the GCM-RCM combination that assumes the smallest temperature increase ( $+2.04\text{ K}$  from the CGCM-WRFG), the mean temperature increase from the suite of 7 NARCCAP models ( $+3.3\text{ K}$ ) and for the GCM-RCM combination that assumes the largest temperature increase ( $+4.23\text{ K}$  from the GFDL-HRM3) (Figure 36).

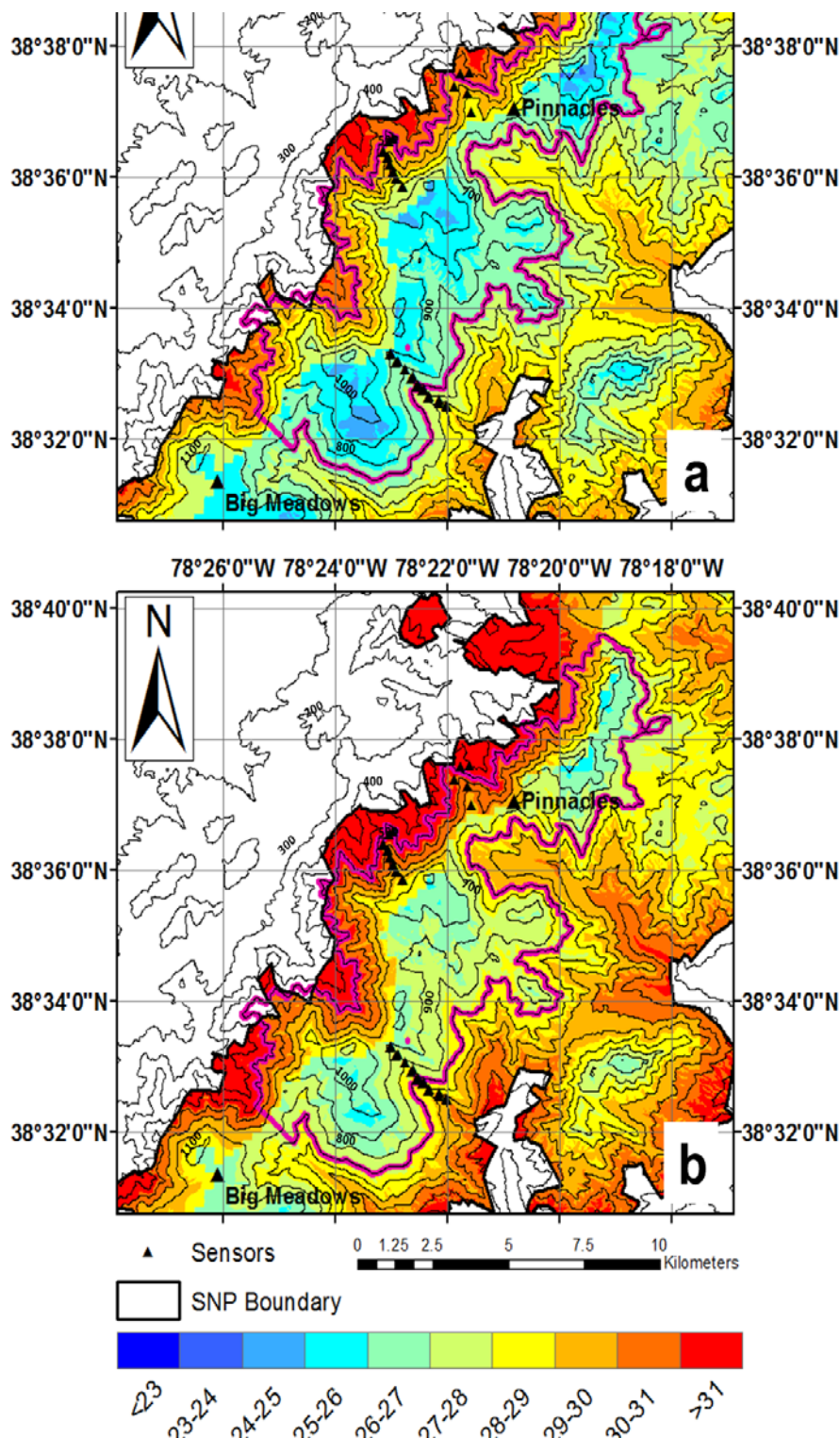


**Figure 36.** 15 m spatial resolution map of future temperatures in SNP in the year 2055 for different NARCCAP scenarios. Panel (a) assumes an increase in July maximum temperature of +2.04 K over present day values, which represents the smallest temperature increase from the suite of 7 NARCCAP GCM-RCMs and is from the CGCM-WRFG model. Panel (b) assumes an increase of 3.3 K, which is the mean temperature increase from the 7 NARCCAP GCM-RCMs.

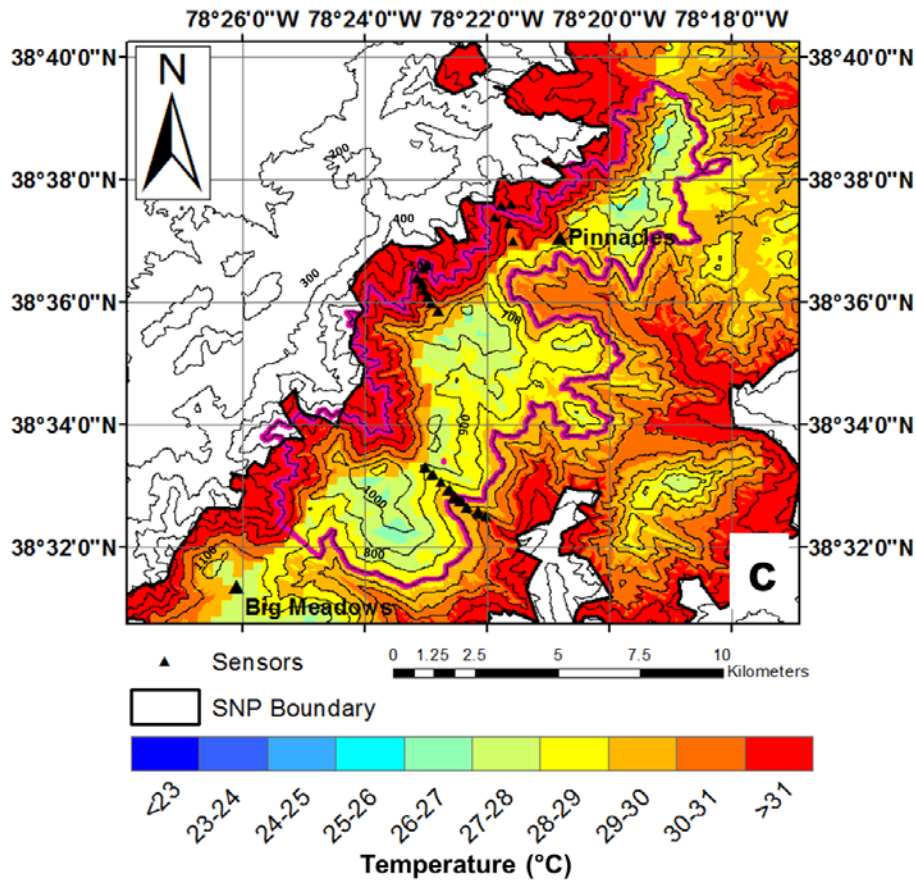


**Figure 36 continued.** Panel (c) projects a temperature increase of 4.23 K, which is the largest temperature increase from the 7 NARCCAP GCM-RCMs and is from the GFDL-HRM3 model. Elevation contours in black every 100 m; black line denotes SNP boundary; magenta line denotes the habitat of *P. shenandoah*; small black triangles indicate locations of HOBOS, large black triangles are labeled and indicate Big Meadows and Pinnacles, respectively.

As the NARCCAP models are one of several climate projections available for the region, we compare the mean projected temperature increase from the suite of 7 NARCCAP RCMs (which use the A1B emissions scenario) with the projected temperature increases from the A1F1 scenario (Figure 37) to show the projected temperature changes in SNP under two different IPCC emissions scenarios.”

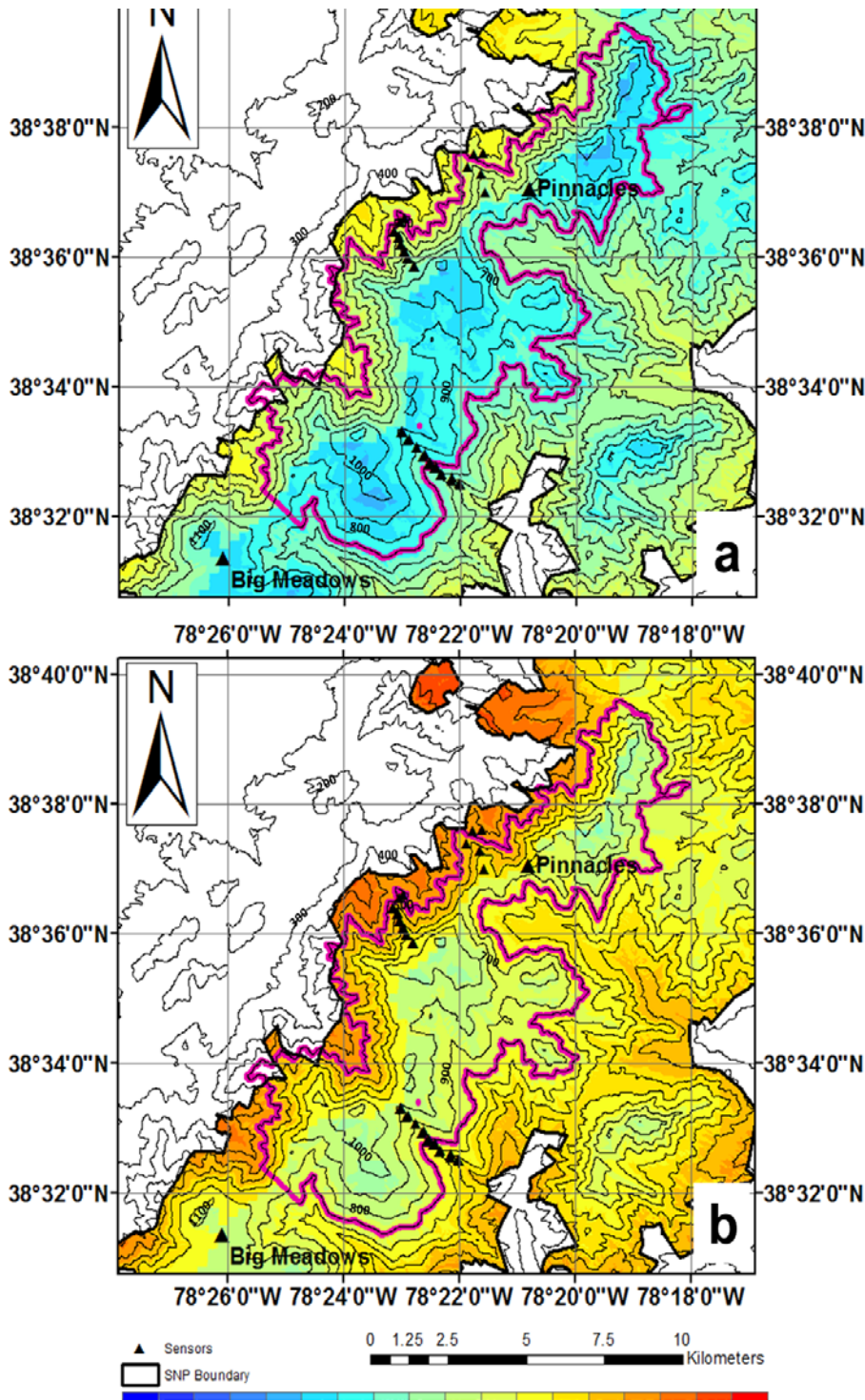


**Figure 37.** 15 m spatial resolution map of future temperatures in SNP in the year 2055 assuming a temperature increase of 3.3°C (average projected temperature increase from NARCCAP RCMs for Big Meadows) to mean July maximum temperatures (a) and a temperature increase of 7.0°C (projected temperature at Big Meadows from the RegCM3 RCM using the SRES A1FI emissions scenario) (b). Elevation contours in black every 100 m; black line denotes SNP boundary; magenta line denotes the habitat of *P. shenandoah*; small black triangles indicate locations of HOBOS, large black triangles are labeled and indicate Big Meadows and Pinnacles, respectively. Note that the color scale is different from Figure 36.



## Conclusions

In the present report, we have summarized the observations, simulations, and data analyses performed by UVA to provide gridded climate maps for present day and for and future climate change projections at fine scales in Shenandoah National Park. We first presented an overview of our statistical and dynamical downscaling approaches, described the observations and models used in our downscaling approaches, and presented our results on present-day temperature variations in SNP and maps of current and projected temperature and precipitation changes within SNP under different climate change scenarios.

We found that presently-available high-resolution gridded climate data sets, such as PRISM and DAYMET, compare favorably with independent, long-term observations from mountaintop climate monitoring stations in SNP (i.e. Pinnacles and Big Meadows). However, directly using output from these models for mountain slopes is inadequate and thus a correction factor is used to downscale present-day temperatures to the region of interest to <1 km spatial resolution. This correction factor is a function of the mean monthly lapse rate and a temperature offset that depends on whether a location is on the west side or the east side of the Blue Ridge, as well as if the slope is oriented to the north or to the south. Important to note, though, is that the use of this correction factor has not been tested outside SNP and thus should not be applied to regions outside the boundaries of SNP.

Compared to the downscaled PRISM results, high-resolution simulations from a state-of-the-art atmospheric model, WRF, shows better agreement with the observations from within SNP. However, subgrid spatial scale variability in moisture variables, such as mean relative humidity and total monthly precipitation, is more difficult than temperature to quantify with gridded climate data sets and numerical models.

From our analyses of RCM output for SNP, we find that mean July maximum temperature is expected to increase at a rate of 0.3-0.6°C per decade, depending on the NARCCAP RCM used. To simulate the projected temperature increase by the suite of NARCCAP RCMs, we recommend applying a temperature increase of 0.47°C per decade, which represents the mean temperature change for Big Meadows for the suite of NARCCAP RCMs. Changes in moisture variables from NARCCAP, e.g. precipitation and humidity, show much less consistency with about half the NARCCAP RCMs suggesting an increase in moisture and the other half indicating decreases in atmospheric moisture.

The above projections represent only one emissions scenario. To represent the most pessimistic climate change scenarios and to get an idea of some of the climate extremes that might be

experienced in the future in SNP, we recommend using the temperature change projections obtained from the RegCM3 RCM that assumes the SRES A1F1 emissions scenario. Applying a 0.7°C temperature increase per decade is recommended to represent this scenario.

Using the aforementioned approaches, we are able to generate high-resolution maps of present-day and projected changes in mean July maximum temperature for the habitat of *P. shenandoah*. The data that were used to produce these maps are available on DVD or from the authors of this report.

## **Publications**

### **Year I**

[none]

### **Year II**

[none]

### **Year III**

Lee, T. R., S. F. J. De Wekker, and J. E. B. Wofford, 2014: Downscaling maximum temperature projections to sub-kilometer resolutions in the Shenandoah National Park of Virginia, USA. *Submitted to Advances in Meteorology.*



## Conference Presentations

### Year I

Lee, T. R. and S. F. J. De Wekker: Temperature variations along slope and ridge locations in the Blue Ridge Mountains and their relationship to temperatures in the free atmosphere, 31<sup>st</sup> International Conference on Alpine Meteorology, 23-27 May 2011, Aviemore, Scotland.

### Year II

Lee, T. R. and S. F. J. De Wekker: Simulating daytime boundary layer heights and mesoscale flows in complex terrain using WRF: a case study for the Virginia Blue Ridge Mountains, WRF Workshop, 25-29 June 2012, Boulder, Colorado.

### Year III

[none]



# Student Reports

## Year I

Brown, Nathan: Temperature and radiation variations at Pinnacles, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Spring, 2011.

Lawrence, Douglas: Testing the accuracy of HOBO Pro v2 temperature and relative humidity sensors, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Fall 2010.

Li, Angang: Climate downscaling in complex terrain: variations at Pinnacles, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Spring 2011.

Muir, Chris: Calibration analysis and initial deployment of HOBO temperature and relative humidity sensors, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Spring 2011.

Stoner, Elizabeth: Downscaling microclimates of Shenandoah National Park, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Fall 2010.

## Year II

Delmar, Sydney: Causes of small-scale temperature variability around Pinnacles, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Fall, 2011.

Nystrom, Amelia: Early morning solar radiation rates as they differ across mountainous terrain: A look at variations in sunrise, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Fall, 2011.

Nystrom, Amelia: Downscaling with PRISM, Independent Study supervised by Stephan F. J. De Wekker and Temple R. Lee, Spring 2012.

## Year III

[none]



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## **Appendix A: Contents of DVD.**

1. Text files containing 10-minute data from the network of HOBO temperature sensors from 1 May 2011 through 1 November 2012.
2. ArcGIS shapefiles of output from the WRF simulations for present-day July maximum temperatures at 1 km spatial resolution for SNP (same as shown in Figure 27).
3. ArcGIS shapefiles of the maps of present-day July maximum temperatures in SNP, as well as projected temperatures for the A1B scenario and A1F1 scenarios, at a 15 m spatial resolution for SNP (same as shown in Figure 36).



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