Agricultural and Forest Meteorology 114 (2003) 141–151

AGRICULTURAL AND FOREST METEOROLOGY

www.elsevier.com/locate/agrformet

Spatial estimation of air temperature differences for landscape-scale studies in montane environments

Todd R. Lookingbill*, Dean L. Urban

Nicholas School of the Environment and Earth Science, Duke University, Durham, NC 27708, USA

Received 18 March 2002; received in revised form 13 August 2002; accepted 17 September 2002

Abstract

Capturing fine-grain environmental patterns at landscape scales cannot be accomplished easily using conventional sampling techniques. Yet increasingly, the landscape is the scale at which ecosystems are managed. Temperature variability is an important control of many ecological processes. Elevation is often used as a proxy for temperature in montane ecosystems, partly because few direct measurements are available. We propose a low-cost and logistically practical approach to collecting spatially explicit temperature data using a network of portable temperature micro-loggers. These data can be used to generate simple, site-specific models for estimating temperature differences across complex terrain. We demonstrate the approach in a predominantly old-growth watershed in the Oregon Western Cascades. Environmental lapse rates are generated for July mean, maximum and minimum temperatures. Temperature estimates are improved substantially over these lapse rate estimates by including measures of relative radiation and relative slope position as additional explanatory variables in the model. The development of temperature estimates that explicitly account for topography has important implications for ecological analysis, which frequently relies upon the simplifying assumptions associated with lapse rates in describing the environmental template.

Keywords: H.J. Andrews Experimental Forest; Lapse rate; Old-growth forest; Temperature modeling; Terrain analysis

1. Introduction

Efforts to describe vegetation patterns in montane systems historically have relied on elevation as an ecological “proxy” variable to represent complex environmental gradients (Whittaker, 1978). While elevation is reasonably correlated with distributions of species, this indirect correlation is unsatisfying. It has been understood for some time that variability in temperature and soil moisture is a major determinant of plant distributions (Whittaker, 1967; Stephenson, 1990). Elevation is merely a convenient way of representing these environmental factors (Barry, 1992). Since the relationships among ecological variables likely will change with any changes in climate, it is important to develop more descriptive models of key ecological constraints such as temperature in order to model future ecological processes.

Attaining data to develop these models is hampered by at least two logistical issues. First, better models are needed at the landscape scale, because this is the level at which management decisions typically are made (Christensen et al., 1996, 2000). Describing complex environmental patterns at this scale can be extremely data intensive. Fine-grain studies are able to capture environmental variability explicitly (e.g. Yeakley et al., 1998; Chen et al., 1999), and much

* Corresponding author. Fax: +1-919-684-8741.
E-mail address: todd.lookingbill@duke.edu (T.R. Lookingbill).

PII: S0168-1923(02)00196-X

of this fine-scaled detail averages out at regional to global scales (e.g. general circulation models, Henderson-Sellers and McGuffie, 1987; VEMAP, 1995). At landscape scales, however, detailed environmental patterns cannot be ignored. Novel sampling techniques often are required to capture fine-scaled detail over large spatial extents (Urban et al., 2000, 2002).

Second, obtaining sufficient data to calibrate and validate temperature models is frequently difficult in montane environments where weather-monitoring stations are sparse (Running et al., 1987; Yeakley et al., 1998). Weather stations tend to be at low elevations in watersheds and therefore tend to overestimate temperature across steep terrain (Phillips et al., 1992; Daly et al., 1994). Working in the southern Appalachian mountains, Bolstad et al. (1998) suggested that spatially extrapolated estimates of temperature from a few low-elevation weather stations are consistently biased due to the inability to account for local topographic effects. Extending the network of monitoring stations to account for these phenomena has been logistically and economically prohibitive (Chen et al., 1999).

Local topography can modify substantially the relationship between elevation and temperature. Primary topoclimatic effects result from differences in hillslope angle and aspect (Barry, 1992). These effects are governed largely by the relationship of slope orientation to solar radiation. In the northern hemisphere, north-facing slopes experience less radiation than south-facing slopes. McCutchan and Fox (1986) showed that aspect differences can be even more important than elevation in controlling temperature. Bolstad et al. (1998) suggested that temperature maxima, in particular, are sensitive to topographic exposure.

Secondary topoclimatic effects can result from the influence of terrain on mountain winds and the generation of airflow effects such as cold air drainage (Barry, 1992). As a result, mountain valleys, mid-slopes, and ridges can be characterized by very different temperature regimes. Evaporative cooling can further accentuate these differences for riparian areas along valley bottoms. While temperature maxima may be particularly sensitive to radiation differences, temperature minima may be more strongly influenced by relative slope position and mountain air currents (Bolstad et al., 1998).

In this analysis, we consider a nested series of temperature regression models. We begin with a simple elevation model, in which we collect data to develop a site-specific lapse rate—a quantitative description of the decrease in temperature with increase in elevation. This first model serves as an improvement over the generic environmental lapse rate of 6 °C/km elevation gain (Barry, 1992). We then consider more complicated models that include measures of relative radiation and relative slope position as additional potential explanatory variables. We test the importance of each factor in explaining temperature means, minima, and maxima.

Ecological predictions that rely upon the loose correlation between vegetation and temperature as proxied by elevation may be adequate for national and regional analyses, but they will not suffice at the landscape scale. The ultimate objective of our research is to isolate the fraction of the ubiquitous elevation gradient (Whittaker, 1967; Kessell, 1979; Stephenson, 1998) that can be attributed to temperature. To do this effectively we must develop an efficient means of including fine-scale topographic effects in our temperature models. This paper addresses the following specific objectives:

1. To develop a site-specific lapse rate model of a mountainous study area.
2. To test this model against increasingly complex models that include fine-scale topographic factors as potential explanatory variables.
3. To test hypotheses that radiation differences strongly influence temperature maxima and relative slope position influences temperature minima.
4. To develop a simple approach to data collection and statistical analysis that could be applied in mountainous study areas to create site-specific temperature models with minimal investment in time and money.

2. Methods

2.1. Study area

Located predominantly in old-growth forest of the Oregon Western Cascades (Fig. 1), the H.J. Andrews Experimental Forest (HJA) is a Long Term Ecological Research (LTER) site covering 6400 ha and

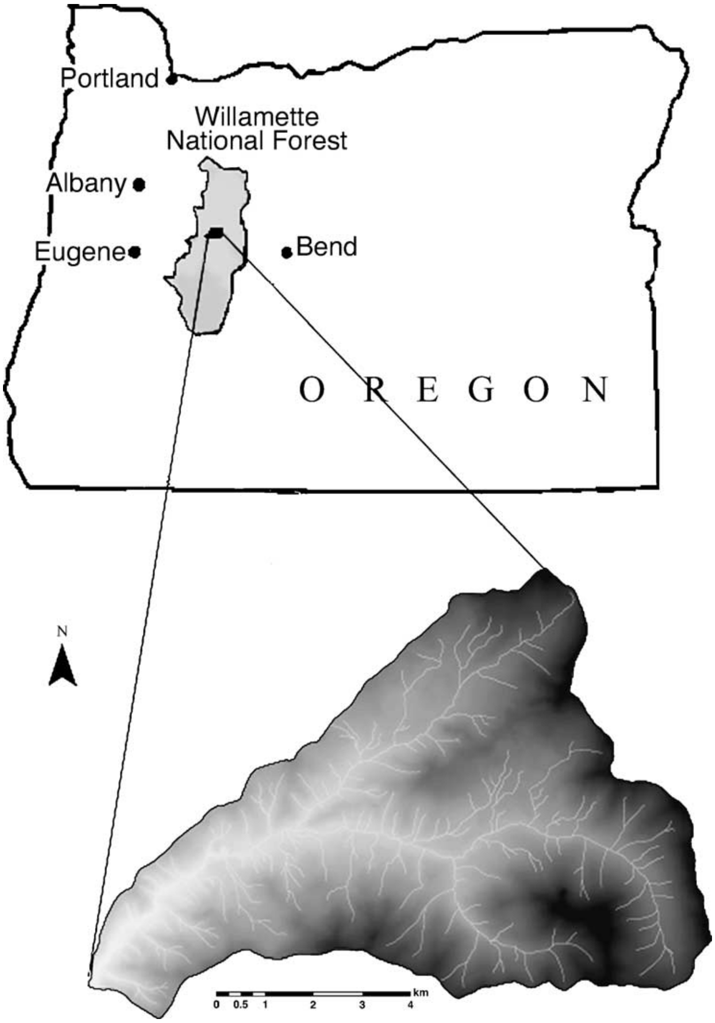

Fig. 1. Locator map for the H.J. Andrews Experimental Forest LTER. The study site is located on the west side of the Cascade mountains approximately 80 km east of Eugene, OR.

ranging in elevation from 410 to 1630 m (McKee, 1998). The HJA was established in 1948 within a forested watershed with about 65% of the land in old-growth (i.e. 400–500 years old). A preliminary vegetation survey of the site suggests that elevation is the primary correlate with community pattern. *Pseudotsuga menziesii* (Douglas-fir), *Tsuga heterophylla* (western hemlock), and *Thuja plicata* (western redcedar) are the dominant species at lower elevations in the forest, while *Abies amabilis* (Pacific silver fir), *A. procera* (noble fir), and *Tsuga mertensiana* (mountain hemlock) dominate upper elevations. Vegetation sampling in the HJA suggests a transition in forest community composition at elevations around 1200 m, consistent with trends found elsewhere in the Oregon Western Cascades (Dyrness et al., 1976; Franklin and Dyrness, 1988).

As an LTER site, the HJA maintains an extensive database of meteorological data (Bierlmaier and McKee, 1989). Climate is characteristic of the Pacific Northwest, with dry summers and wet, mild winters. Only about one-tenth of the annual precipitation falls from June to September in the Western Cascades (Daly et al., 1994). At larger scale, Greenland (1994) has placed the climate of the HJA into a regional context based on monthly temperature and precipitation data. Sea and Whitlock (1995) have reconstructed the vegetational and climatic history of the region and suggested that vegetation changes have been influenced heavily by changes in temperature over the past 14,000 years.

2.2. Data

Temperature measurements were recorded hourly using a sampling network of portable temperature micro-loggers (HOBO: Onset Computer Corporation). The micro-loggers were hung from trees at a height of 1.3 m above ground level. Sensors were kept on the northwest side of trees to minimize exposure to direct radiation. All measurements were taken in undisturbed, old-growth forest in an effort to control biotic variability, while varying only topographic factors. Stand variation in stem density and total basal area was minimized. Relative temperature differences, therefore, should be applicable across the old-growth components of the landscape. While absolute temperatures may not reflect accurately temperatures experienced in tree canopies or by regeneration on the forest floor, relative differences should be scalable to the different vertical strata of old-growth forests.

Data were gathered for the month of July over two successive years in 1999–2000. In examining the existing meteorological network at the HJA, Rosentrater (1997) identified the late spring/early summer as the time of greatest temperature spatial and temporal variability. Greene and Klopsch (1985) also choose July as a key month for developing their lapse rate models for Mount Rainier National Park in the Washington Cascade Range.

Two year-long datalogger stations (CR10X: Campbell Scientific Incorporated) were linked to the temporary networks by placing micro-loggers at each of the permanent datalogger stations in both 1999 and 2000 (Fig. 2). The dataloggers recorded measurements from temperature probes (CS107: Campbell Scientific Incorporated), which also were located at 1.3 m above ground but protected in louvered radiation shields open to the environment. These continuous records provide the potential of extending the July micro-logger trends over a longer time frame. Measurements taken by the two sampling devices were highly correlated at both the high elevation (1292 m) and low elevation (642 m) locations (Fig. 3). The micro-logger data were, on average, 0.2 °C higher for the low elevation site and 0.3 °C higher for the high elevation site.

Models were developed using data from 45 micro-loggers deployed over the summer of 2000. A stratified sampling design was used, whereby sample locations where stratified across elevation, aspect and relative slope position for each of seven major watersheds of the HJA determined by geographic information systems analysis (Fig. 2A). These factors represent the predominant altitudinal and topoclimatic controls on temperature (Barry, 1992). Aspect is associated with differences in relative radiation load, while relative slope position is associated with airflow effects such as cold air drainage. Additional data were available from 33 micro-loggers deployed across the watershed over the summer of 1999 (Fig. 2B). These data were used for validation purposes. The locations of the micro-loggers in 1999 overlapped with the 2000 locations only at the permanent CR10X datalogger stations and at the HJA's primary meteorological station at the base of the watershed.

2.3. Analysis

The monthly average, daily minimum, and daily maximum temperatures were calculated for each location from the hourly measurements. The 2000 data were used to compare a series of increasingly more complex regression models attempting to describe temperature differences across the watershed. The models were nested so they could be compared by simple likelihood ratio tests (Sokal and Rohlf, 1995). Variables were added to the models in order of increasing explanatory power until additional variables no longer significantly improved the model.

Each of the variables chosen as a candidate for the models was selected because of its potential influence on temperature. Additionally, all of the variables could be derived easily from commonly available geographic information systems data (e.g. digital elevation model (DEM), streams coverage). Besides elevation, we considered relative slope position,

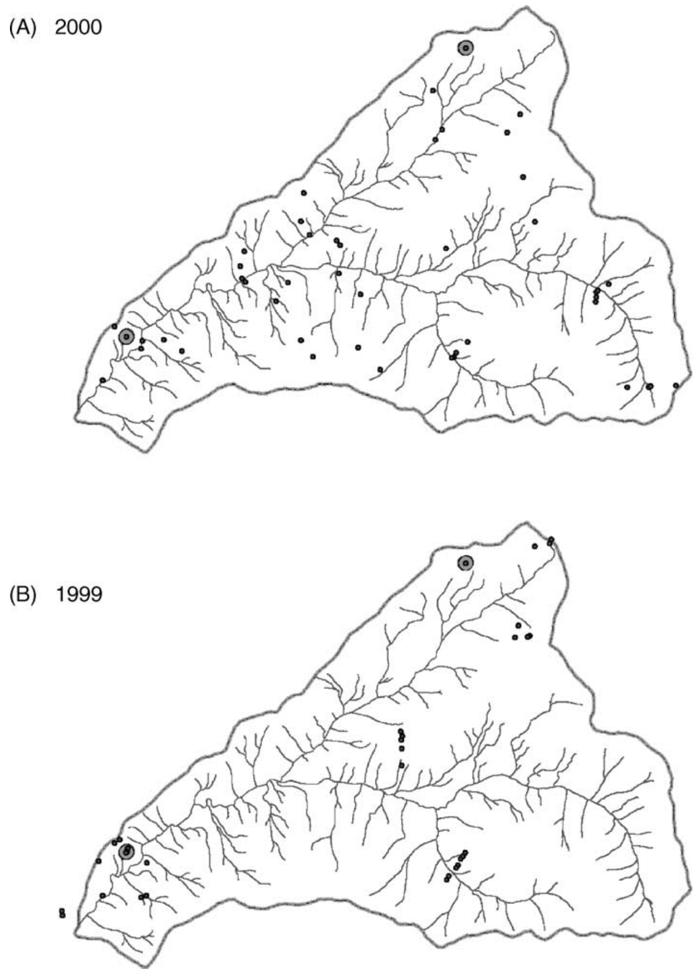

Fig. 2. (A) Locations of 45 micro-loggers for July 2000. (B) Locations of 33 micro-logger locations for 1999. Larger circles represent locations of permanent CR10X stations.

distance from stream (log transformed because the strength of the relationship decreases with distance), and a wide range of radiation proxies ranging from simple transformed aspect (Beers et al., 1966) to a potential relative radiation (PRR) measure developed from DEM data. Pierce et al. (2002) describe the radiation proxies in detail. The PRR index, developed specifically for use in community level vegetation analysis, is a measure of how topography translates to spatial differences in relative radiation. It both accounts for hillshading and shadowing effects and integrates over time to account for the fact that solar position changes over the course of the day and year.

Once models were calibrated, they were confronted with the 1999 data as a validation exercise. Models therefore were evaluated in terms of their ability to describe the 2000 data from which they were generated and their ability to predict temperature differences in the 1999 data attained from different sampling locations and a different year. Using data from separate years for calibration and validation purposes was a practical decision. By redeploying the same micro-loggers for a second time in order to gather sufficient data for model testing, we were able to reduce greatly the cost of the analysis.

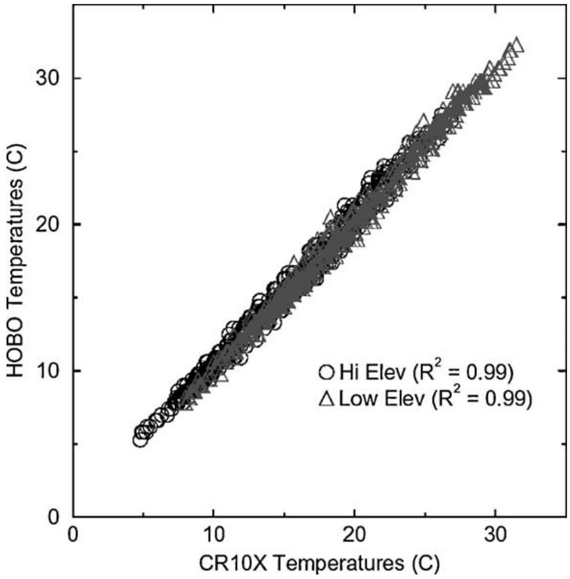

Fig. 3. Comparison of 1999 temperature data collected from micro-loggers with data collected from two CR10X dataloggers. The high elevation site was located at 1292 m. The low elevation site was located at 642 m ($n = 744$ hourly measurements at each site). $R^2 = 0.99$ for both sites.

3. Results

3.1. Model fits

Mean July temperatures ranged from 12.9 to 17.6 °C at the 45 sites sampled in 2000. In order of increasing complexity, the three best models for predicting mean July temperature are as follows:

$$\hat{y} = \beta_0 + \beta_1 \,\text{elevation} + \varepsilon \quad (1)$$

$$\hat{y} = \beta_0 + \beta_1 \,\text{elevation} + \beta_2 \log(d_{\text{strm}}) + \varepsilon \quad (2)$$

$$\hat{y} = \beta_0 + \beta_1 \,\text{elevation} + \beta_2 \log(d_{\text{strm}}) + \beta_3 \,\text{radiation} + \varepsilon \quad (3)$$

where $\hat{y}$ is the estimated mean temperature, β's are constants, d_{strm} is the distance from the nearest stream in meters, radiation is our DEM derived estimate of potential relative radiation (PRR index), and ε is an error term. Other variables considered do not improve the model fit.

Elevation, which ranges from 433–1359 m, is the explanatory variable best able to explain the differences in mean temperature among the sites. This case mimics a traditional lapse rate model where elevation can be viewed as the primary forcing variable in the system. Local effects, as captured by the distance from stream and radiation terms, are also important. Model 2 is a significant improvement over Model 1 (F-statistic $= 39.79$, $P < 0.001$). Model 3 is able to describe the spatial variability in temperature slightly better than Model 2 (F-statistic $= 3.80$, $P = 0.058$).

The spatial residuals from each of the three models are shown in Fig. 4. Model 1, the elevation model, does a reasonable job of fitting the data, but with 19 of the 45 points over- or underestimated by greater than 0.5 °C. Adding distance to stream to the model reduces this number to 10. In particular, the model fit is improved for many of the sites in the higher-elevation, eastern portion of the study area. Adding radiation to the model further reduces to six the number of points over- or underestimated by greater than 0.5 °C. This factor seems to be more important to the lower-elevation, western portion of the watershed with more deeply incised stream channels.

For daily maximum temperature, the simple lapse rate model is significantly improved upon by including radiation as estimated by Beers et al. (1966) transformed aspect as an additional explanatory variable (Table 1). Relative slope position as measured by distance from stream has little effect.

In contrast, distance from stream is more important than any of the radiation proxies in explaining variability in daily minimum temperature (Table 1). The combination of distance from stream and elevation provides the most parsimonious model. Radiation differences have little effect on minimum temperatures.

3.2. Model validations

The model validations confirm that mean temperature can be better described using a combination of elevation and fine-scale environmental variables than it can by using elevation alone. An analysis of the bias and spread of the predictions can be made by graphing the predicted against the observed values (Fig. 5). The one-to-one line on this graph represents a perfect fit of the data to the model. Points above this line were warmer than predicted by the model; points below this line were cooler than predicted by the model. The scatter of points around the one-to-one line represents the

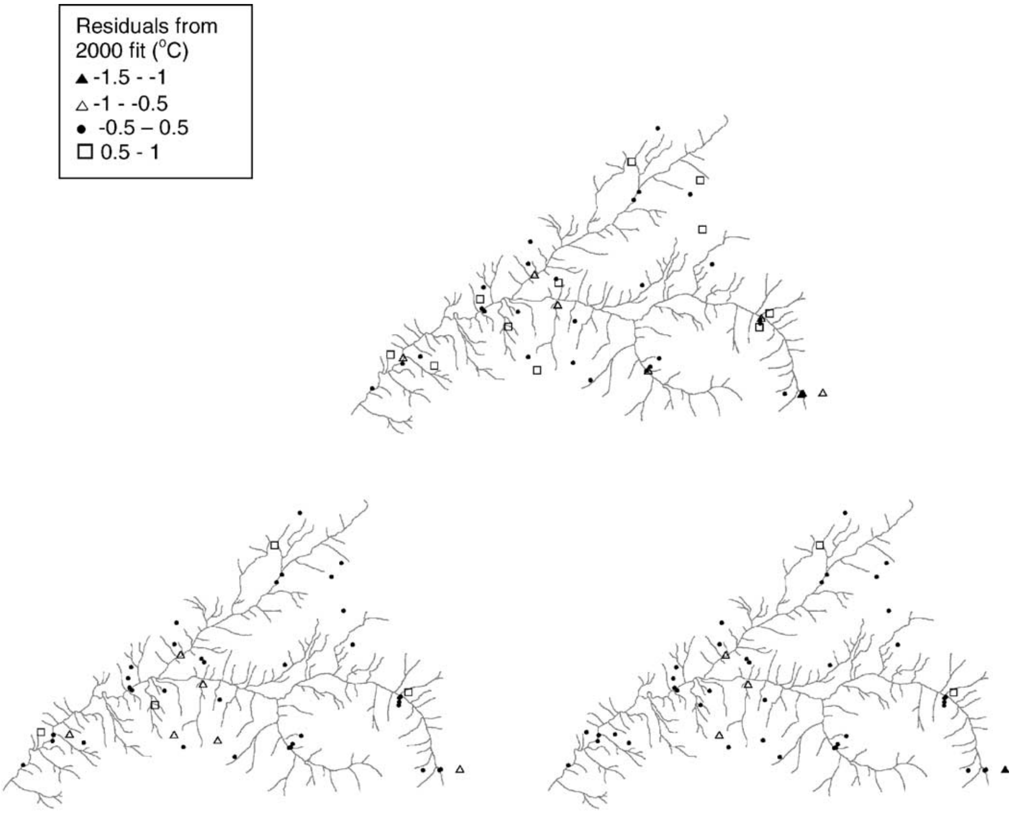

Fig. 4. Maps of spatial residuals for the mean July temperature models. Squares represent locations that were warmer than predicted by the models by at least 0.5 °C. Triangles represent locations that were cooler than predicted by the models by at least 0.5 °C.

Table 1
Monthly average, daily maximum and daily minimum temperatures were modeled for July 2000

	R^2	*F*-statistic	*P*-value
Mean temperature			
Model 1: mean temperature = *f*(elevation)	0.82	189.56	<0.001
Model 2: mean temperature = *f*(elevation, log(d_{strm}))	0.90	36.79	<0.001
Model 3: mean temperature = *f*(elevation, log(d_{strm}), radiation)	0.91	3.80	0.058
Daily maximum temperature			
Model 1: maximum temperature = *f*(elevation)	0.41	30.30	<0.001
Model 2: maximum temperature = *f*(elevation, radiation)	0.48	5.74	0.020
Model 3: maximum temperature = *f*(elevation, radiation, log(d_{strm}))	0.49	0.13	0.725
Daily minimum temperature			
Model 1: minimum temperature = *f*(elevation)	0.58	59.98	<0.001
Model 2: minimum temperature = *f*(elevation, log(d_{strm}))	0.67	11.77	0.001
Model 3: minimum temperature = *f*(elevation, log(d_{strm}), radiation)	0.67	0.002	0.965

Variables were added to the models in order of increasing explanatory power until additional variables no longer significantly improved the model fit.

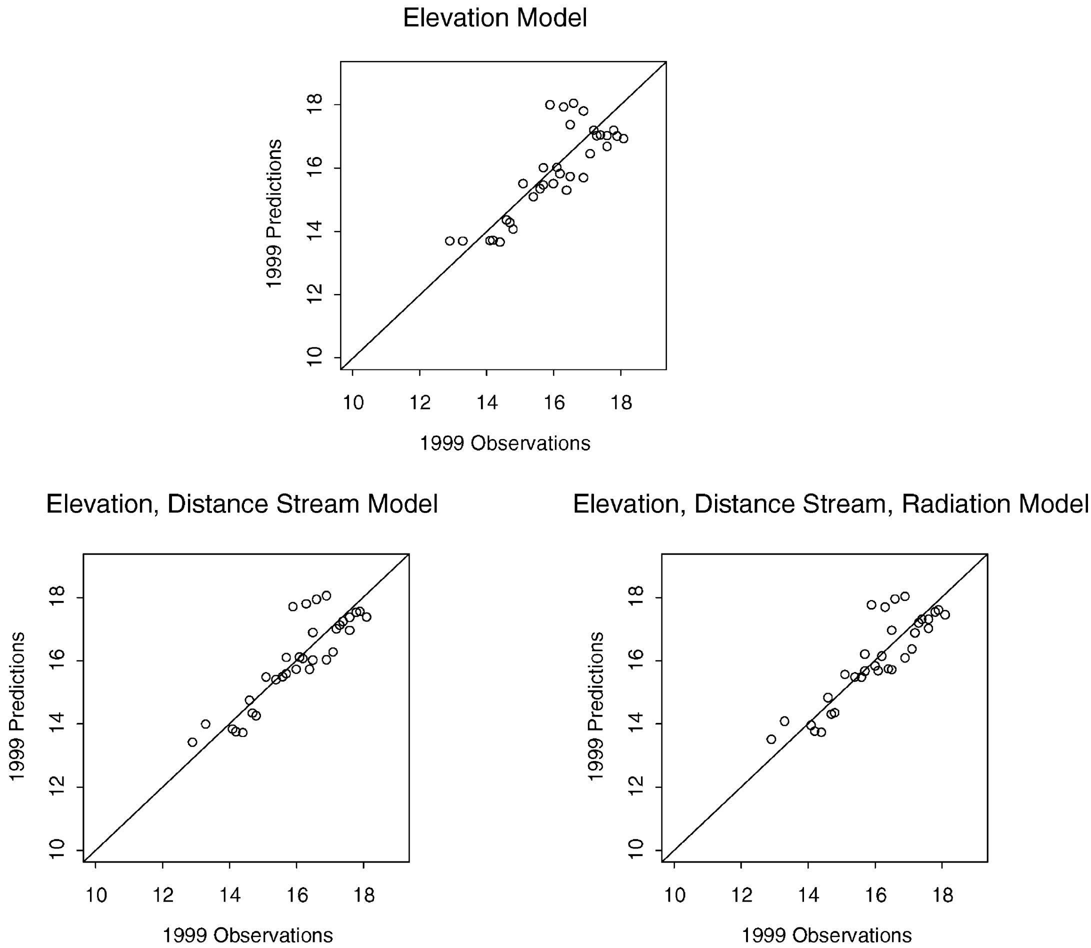

Fig. 5. Comparison of the ability of the models calibrated with 2000 data to explain relative differences in 1999 temperatures. Predictions that match observations exactly would be on the one-to-one line.

spread of the error. Although there is not a systematic bias in any of the models, the spread is reduced in the more detailed models (mean square error of the predictions (M.S.E.) = 0.66 for elevation alone versus M.S.E. = 0.44 and 0.45 for the other two models).

4. Discussion

It has been argued that temperature is the single most important component of mountain climate (e.g. Barry, 1992). Detailed temperature data certainly are required to understand plant community dynamics. Among the long list of ecological processes influenced by temperature are photosynthesis, evapotranspiration, respiration, carbon fixation and decomposition (Running et al., 1987; Bolstad et al., 1998). Potential applications of improved temperature estimates covering a variety of spatial scales include studies of global climate change, global vegetation dynamics, regional hydrologic balances, and local photosynthesis and transpiration capabilities (Running et al., 1987; Miller and Urban, 1999). It is at the landscape scale that our current climate models are particularly insufficient (Chen et al., 1999). With the growing popularity of geographic information systems, the demand for regularly distributed meteorological information is likely only to increase (Daly et al., 1994).

Unfortunately, the data typically do not exist to develop detailed temperature models in montane study areas. For most systems, available data are limited to a small number of base station measurements. Further, these base stations are typically situated at locations that are not representative of the landscape as a whole (Phillips et al., 1992). The use of inexpensive, portable micro-loggers allowed us to collect data and model temperature over a large spatial coverage given practical economic, time and human resource constraints.

Although more expensive recording devices are available, we found the relatively low-end micro-loggers to be sufficient for our purposes. Agreement between micro-logger and permanent datalogger measurements were good, although the micro-loggers showed a slight tendency to heat up more slowly in the morning and retain heat longer into the afternoon and evening. This observed lag was likely due to differences in the weatherproofing of the sensors rather than any differences between the recording equipment. The plastic weatherproofing containers holding the micro-loggers may have created a slight greenhouse effect around the sensors. For a small increase in cost, weatherproof micro-loggers could be purchased, thus removing the need for the plastic containers. Protective containers also could be designed that are partially open to the atmosphere and would experience less of a greenhouse effect. Since we observed primarily a slight lag in the timing of temperature changes and little difference between the mean, daily maximum or daily minimum measurements, we do not feel that the use of the weatherproof containers substantially influenced our results.

Use of the micro-loggers allowed us to generate site-specific lapse rates for July temperature means, maxima, and minima across the HJA. The mean temperature lapse rate (4.5 °C/km) and maximum temperature lapse rate (7.0 °C/km) are similar to the generic environmental lapse rate of 6 °C/km. Given that the study area covers little more than a km of elevation change, our equations differ from the generic lapse rate in their predictions by no more than 1–2 °C. The influence of elevation on temperature minima, however, is less severe (3.8 °C/km). The finding of a lower lapse rate for temperature minima than for other measures of temperature is in agreement with others who have examined these relationships at a much larger spatial scale for the northwestern US (Thornton et al., 1997).

The results of our analysis suggest that temperature estimates that consider additional fine-scale topographic variability describe temperature more accurately for our study area than do estimates derived from simple lapse rate models. The lapse rate approach completely ignores local effects associated with differences in aspect and relative slope position. As shown here, these factors can have measurable effects on temperature. Our results are consistent with others who found daily minima to be influenced heavily by relative slope position and daily maxima to be more affected by topographic exposure (Bolstad et al., 1998). Both types of effects influence mean temperatures.

It is important to emphasize that the results presented in this analysis are applicable to only a very narrow range of conditions. As with any statistical model, these models should not be extrapolated beyond the range of conditions specified by the input data. These include the topographic and climatic conditions of the study area, the timing of the sampling in mid-summer, and the stand structure of old-growth forest. Further, the absolute temperatures derived from measurements taken at 1.3 m above ground may not be the values most directly relevant to tree growth or reproductive success, but the relative temperature differences between different locations within the landscape should be robust across different vertical strata. For many ecological applications, it is these relative differences that are of primary interest. For example, we developed these models to help explain transitions in community composition for old-growth forests of the HJA. These transitions are more strongly correlated with our model predictions of relative July temperature differences than any single temperature "proxy" variable (e.g. elevation, slope, aspect: Lookingbill, unpublished data).

Though the results themselves may have limits on their applicability, the approach is widely applicable. The sensors are relatively inexpensive and minimal labor is involved in deploying and downloading data. With some attention paid to sample design a priori, statistical analysis and model generation should follow easily. We have applied the techniques described in this paper to other study sites with success (e.g. Kaweah Basin of Sequoia National Park: Pierce, 2002).

Since temperature is such an important component of mountain climate, we suggest that developing a simple geographic model of temperature differences should be an important first-step in many landscape-scale ecological studies. Our approach offers an economic means of quickly assessing spatial temperature trends for topographically complex environments.

Acknowledgements

This research benefited greatly from discussions with Ken Knoerr, David Greenland, Julia Jones, Fred Swanson, and Ken Pierce. Field assistance was provided by Rachel Tallmadge and Andrew Black. The research presented here is part of a project on Pacific Northwest old-growth forest dynamics partially funded by a Sigma Xi Grant in Aid of Research and a National Science Foundation Dissertation Improvement Grant to Todd R. Lookingbill. Support also was provided by National Science Foundation Award IBN-9652656 to Dean L. Urban.

References

Barry, R.G., 1992. Mountain Weather and Climate. Routledge, London.

Beers, T.W., Dress, P.E., Wensel, L.C., 1966. Aspect transformation in site productivity research. J. For. 64, 691–692.

Bierlmaier, F.A., McKee A., 1989. Climatic Summaries and Documentation for the Primary Meteorological Station, H.J. Andrews Experimental Forest, 1972–1984. General technical report PNW-GTR-223. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR, USA, 26 pp.

Bolstad, P.V., Swift, L., Collins, F., Regniere, J., 1998. Measured and predicted air temperatures at basin to regional scales in the southern Appalachian mountains. Agric. For. Meteorol. 91, 161–176.

Chen, J., Saunders, S.C., Crow, T.R., Naiman, R.J., Brosofske, K.D., Mroz, G.D., Brookshire, B.L., Franklin, J.F., 1999. Microclimate in forest ecosystem and landscape ecology. BioScience 49, 288–297.

Christensen, N.L., Bartuska, A.M., Brown, J.H., Carpenter, S., D'Antonio, C., Francis, R., Franklin, J.F., MacMahon, J.A., Noss, R.N., Parsons, D.J., Peterson, C.H., Turner, M.G., Woodmansee, R.G., 1996. The report of the Ecological Society of America committee on the scientific basis for ecosystem management. Ecol. Appl. 6, 665–691.

Christensen, N.L., Gregory, S.V., Hagenstein, P.R., Heberlein, T.A., Hendee, J.C., Olson, J.T., Peek, J.M., Perry, D.A., Schowalter, T.D., Sullivan, K., Tilman, G.D., Vogt, K.A., 2000. Environmental Issues in Pacific Northwest Forest Management. National Academy Press, Washington, DC.

Daly, C., Nielson, R.P., Phillips, D.L., 1994. A digital topographic model for distributing precipitation over mountainous terrain. J. Appl. Meteorol. 33, 140–158.

Dyrness, C.T., Franklin, J.F., Moir, W.H., 1976. A Preliminary Classification of Forest Communities in the Central Portion of the Western Cascades in Oregon. Bulletin no. 4. Coniferous Forest Biome, Ecosystem Analysis Studies, US/International Biological Program.

Franklin, J.F., Dyrness, C.T., 1988. Natural Vegetation of Oregon and Washington. Oregon State University Press, Corvallis.

Greene, S.E., Klopsch, M., 1985. Soil and air temperatures for different habitats in Mount Rainier National Park. Research paper PNW-342. USDA, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland, OR, USA.

Greenland, D., 1994. The Pacific Northwest regional context of the climate of the H.J. Andrews Experimental Forest. Northwest Sci. 69, 81–96.

Henderson-Sellers, A., McGuffie, K., 1987. A Climate Modelling Primer. Wiley, New York.

Kessell, S.R., 1979. Gradient Modeling: Resource and Fire Management. Springer, Berlin.

McCutchan, M.H., Fox, D.G., 1986. Effect of elevation and aspect on wind, temperature and humidity. J. Clim. Appl. Meteorol. 25, 1996–2013.

McKee, A., 1998. Focus on field stations: H.J. Andrews Experimental Forest. Bull. Ecol. Soc. Am. 79, 241–246.

Miller, C., Urban, D.L., 1999. Fire, climate and forest pattern in the Sierra Nevada, California. Ecol. Model. 114, 113–135.

Phillips, D.L., Dolph, J., Marks, D., 1992. A comparison of geostatistical procedures for spatial analysis of precipitation in mountainous terrain. Agric. For. Meteorol. 58, 119–141.

Pierce, K.B., 2002. Reconciling forest demography with gradient analysis in montane landscapes, PhD thesis. Nicholas School of the Environment and Earth Sciences, Duke University, Durham, NC, USA.

Pierce, K.B., Lookingbill, T.R., Urban, D.L., 2002. A simple method for estimating potential relative radiation for digital terrain. Landscape Ecol. (submitted for publication).

Rosentrater, L.D., 1997. The thermal climate of the H.J. Andrews Experimental Forest, Oregon, Masters thesis. Department of Geography, University of Oregon, Eugene, OR, USA.

Running, S.W., Nemani, R.R., Hungerford, R.D., 1987. Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. Can. J. For. Res. 17, 472–483.

Sea, D.S., Whitlock, C., 1995. Postglacial vegetation and climate in the Cascade Range, Central Oregon. Q. Res. 43, 370–381.

Sokal, R.R., Rohlf, R.J., 1995. Biometry, third ed. Freeman, San Francisco.

Stephenson, N.L., 1990. Climatic controls on vegetation distribution: the role of the water balance. Am. Nat. 135, 649–670.

Stephenson, N.L., 1998. Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. J. Biogeogr. 25, 855–870.

Thornton, P.E., Running, S.W., White, M.A., 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. J. Hydrol. 190, 214–251.

Urban, D.L., Miller, C., Halpin, P.N., Stephenson, N.L., 2000. Forest gradient response in Sierran landscapes: the physical template. Landscape Ecol. 15, 603–620.

Urban, D., Goslee, S., Pierce, K., Lookingbill, T., 2002. Extending community ecological analyses to landscape scales: a multi-phased approach based on distance measures. Ecoscience 9, 200–212.

VEMAP participants (Melillo, J.M., and 26 others), 1995. Vegetation/ecosystem modeling and analysis project (VEMAP): comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. Global Biogeochem. Cyc. 9, 407–437.

Whittaker, R.H., 1967. Gradient analysis of vegetation. Biol. Rev. 42, 207–264.

Whittaker, R.H., 1978. Ordination of Plant Communities. Handbook of Vegetation Science, vol. 5, second ed. Junk, The Hague.

Yeakley, J.A., Swank, W.T., Swift, L.W., Hornberger, G.M., Shugart, H.H., 1998. Soil moisture gradients and controls on a southern Appalachian hillslope from drought through recharge. Hydrol. Earth Sys. Sci. 2, 41–49.