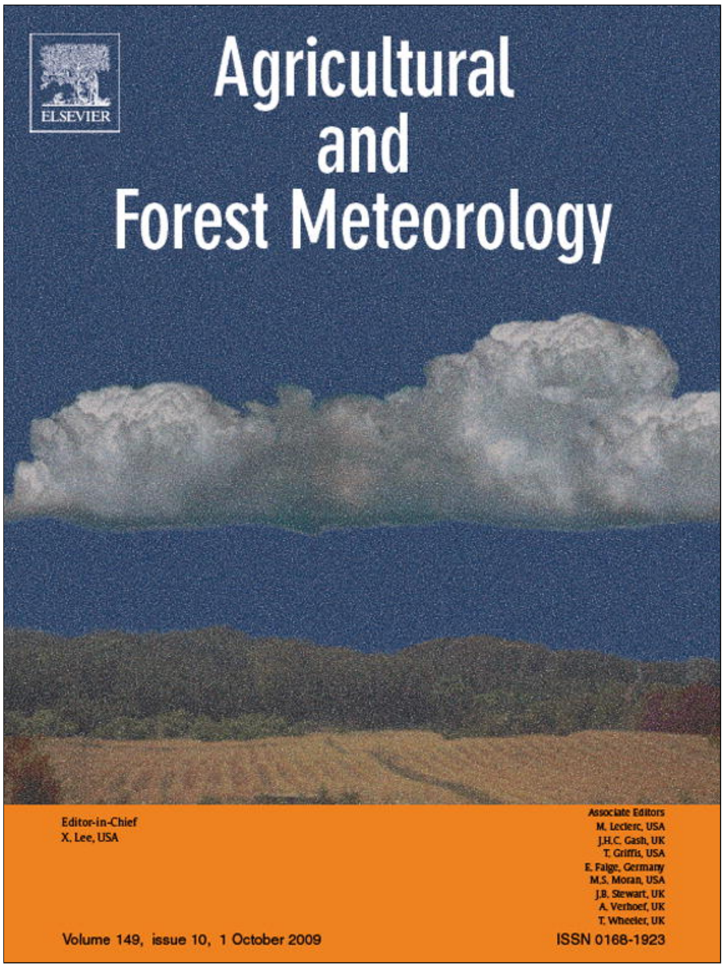
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How much influence does landscape-scale physiography have on air temperature in a mountain environment?

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ABSTRACT

Spatio-temporal patterns of temperature in mountain environments are complex due to both regional synoptic-scale and landscape-scale physiographic controls in these systems. Understanding the nature and magnitude of these physiographic effects has practical and theoretical implications for the development of temperature datasets used in ecosystem assessment and climate change impact studies in regions of complex terrain. This study attempts to quantify the absolute and relative influence of landscape-scale physiographic factors in mediating regional temperatures and assess how these influences vary in time. Our approach was to decompose the variance in *in situ* temperature measurements into components associated with regional free-air temperature estimates and local physiographic effects. Near-surface air temperature data, collected between 1995 and 2006 from 16 meteorological stations in the Lake Tahoe region of California, USA were regressed against free-air temperature (North American Regional Reanalysis dataset) for the same period. Residuals from this fit represent spatial deviations from the regional mean and were modeled as a function of physiographic position on the landscape using variables derived from terrain analysis techniques. Linear models relating temperature residuals to physiographic variables explained roughly 10–90% of the variance in temperature residuals and had root mean squared error of 1.2–2.0 °C, depending upon the type of measurement and time of year. Results demonstrate that: (1) regional temperature patterns were the principle driver of surface temperatures explaining roughly 70–80% of the variance in *in situ* measurements; (2) the remaining variance was largely explained by spatial variability in landscape-scale physiographic variables; (3) the influence of physiographic drivers varied seasonally and was influenced by regional conditions. Periods of well-mixed atmospheric conditions lend themselves to the use of simple elevation-based lapse rate models for temperature estimation whereas other physiographic effects become more prominent during periods of enhanced atmospheric stability; and lastly (4) small differences in temperature due to landscape position, when integrated over time, can have a prominent effect on water balance and thus hydrologic and ecologic processes.

1. Introduction

1.1. Overview

Air temperature is arguably the single most important component of mountain climate (Barry, 1992; Lookingbill and Urban, 2003), influencing a broad range of ecosystem processes including, evapotranspiration, photosynthesis, respiration, decomposition, and carbon fixation, among others (Coughlan and Running, 1997; Running et al., 1987). Through these processes, temperature affects vegetation dynamics and the distribution of biota in space and time. Consequently, temperature shifts and their concomitant ecological effects are increasingly a focal point of climate change impact assessment studies and resource decision-making processes (Millar et al., 2007).

Given critical temperature thresholds for many ecological and hydrologic processes [e.g. snow melt, degree-day accumulation, bud burst, frost tolerance (Cayan et al., 2001; Gutschick and BassirRad, 2003; Inouye, 2000; Saxe et al., 2001; Stewart et al., 2004)], it is vital to be able to accurately represent temperature across the landscape both today, and under future climate scenarios. Modeling of temperature fields is conducted using a multitude of approaches varying from simple linear transforms of elevation to mechanistic approaches. Datasets and modeling

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approaches have assumptions, inherent spatial and temporal resolutions and domains, as well as strengths and weaknesses when applied to specific applications (Beniston et al., 1997; Daly, 2006). In particular, the adequacy of a given dataset becomes increasingly uncertain as spatial resolution becomes finer and terrain becomes more complex (Daly, 2006; Lookingbill and Urban, 2003).

Spatio-temporal patterns of temperature in mountain environments are particularly complex due to both regional and landscape-scale physiographic controls in these systems. By regional controls, we are referring to the combined influence of daily synoptic-scale circulation patterns and large-scale physiographic features such as proximity to oceans, and latitudinal position. This is in contrast to landscape-scale influences on temperature which are mediated by fine-scale physiographic features resolved at the scale of individual watersheds. These include elevation, slope and aspect effects on solar insolation, topographic convergence, and others. Much work has highlighted the influence of regional-scale physiography on climate patterns (Daly, 2006; Daly et al., 2008). Similarly, landscape-scale studies have highlighted the influence of local physiography on temperature patterns (Chung et al., 2002; Chung and Yun, 2004; Lookingbill and Urban, 2003). There has been less work that tries to link the two by quantifying the proportion of the spatial and temporal variance in temperature that can be attributed to local vs. regional drivers, and how these influences vary in time. To these ends, we ask a basic yet fundamental question: *How much influence does landscape-scale physiography have on air temperature*? If these physiographic effects are large, then failing to account for them will result in a discrepancy between the scale of support of *in situ* ecological data and climate data used in a given analysis. In contrast, if these physiographic effects are small, then coarser-scaled climate data should adequately characterize local conditions and prove useful in ecological studies.

1.2. Topoclimate

Topoclimatic modeling refers to spatial estimates of climate that take into account topographic position in the landscape (Lookingbill and Urban, 2003). Physiographic factors such as elevation, slope, aspect, and landscape position influence meteorological elements such as air temperature, precipitation, wind, solar insolation, evapotranspiration, surface flow, snow accumulation and melt, among others (Coughlan and Running, 1997; Thornthwaite, 1953; Weiss et al., 1988). Primary topoclimatic effects include the influence of elevation, hillslope angle and aspect, while secondary effects include terrain effects on winds and cold-air drainage (Barry, 1992; Bolstad et al., 1998). There have been notable efforts at modeling topoclimatic effects. For example, at the watershed scale Lookingbill and Urban (2003) and Chung et al. (2002) showed that minimum temperature estimates could be improved by using distance to streams and flow accumulation as predictor variables to capture the effect of cold-air drainage. At regional scales, the Parameter-elevation Regression on Independent Slopes Model [PRISM—(Daly et al., 2008)] uses a two-layer atmospheric model to stratify stations into those below and above inversion layers. Additionally, modeled estimates of solar insolation have been used effectively as predictors in estimating temperature in complex terrain (Chung and Yun, 2004; Lookingbill and Urban, 2003). Many of these landscape-scale studies have relied on the use of dense networks of portable micro-loggers. The availability of these sensors has provided valuable insights into fine-scale spatial variability in temperature but they also tend to limit analysis periods to short temporal extents [e.g. July temperatures—(Lookingbill and Urban, 2003)] which can obscure linkages between local temperature patterns and regional drivers.

1.3. Objectives

The primary goal of this study is to quantify the absolute and relative influence of landscape-scale physiographic factors on air temperature in an area of complex terrain. Topoclimatic effects operate against a backdrop of regional circulation patterns that vary in time. Hence, a second objective is to examine how the influence of local physiography varies temporally. Understanding the nature and magnitude of these physiographic effects has practical and theoretical implications for the development of temperature datasets used in ecosystem assessment and climate change impact studies in regions of complex terrain.

2. Methods

2.1. Study area

The Lake Tahoe region spans both states of California and Nevada, USA between the Carson and Sierra Nevada mountain ranges (Fig. 1). The total land area in our study area is approximately 2752 km^2 (273,000 ha). The region is ideally suited for this type of research given its diverse physiography, and the presence of a dense network of long-term meteorological stations. The elevation of the region ranges between 1500 m (a.s.l.) to 3400 m (a.s.l.) at the highest peaks. The mean winter temperature at lake level is $-6\,^{\circ}C$; the mean summer temperature is $24\,^{\circ}C$. Annual precipitation ranges from 500 to 1500 mm depending on elevation and location, two-thirds of which falls between December and March as snow (Rogers, 1974). The majority of the region spans the montane and subalpine elevation ranges. Vegetation types are diverse and include conifer dominated forests, both evergreen and deciduous shrublands, as well as diverse meadow and fen habitats.

2.2. Data

Daily near-surface (2 m) temperature means, minima, and maximums were acquired from 16 permanent meteorological stations (14 SNOTEL sites, National Resource Conservation Service; 2 National Weather Service's Cooperative Observer Program sites; Fig. 1). The period of record for the stations varied. For 12 of the sites, a continuous 11-year series was extracted between 1995 and 2006 whereas the remaining stations had a 4-year record (2003–2006). Subsequent analysis was conducted on monthly climate normals (see below); thus, we assume that potential bias introduced by inter-annual variability in station records will occur independent of station physiographic setting (the focus of this study). Extreme outliers were screened by identifying observations that were >3 standard deviations from the means of all observations across all sites. Topographic data used in the analysis was derived from a 30 m USGS digital elevation model (DEM).

2.3. Decomposing temperature variance into synoptic and local effects

Our overall approach is to decompose the variance in *in situ* temperature measurements into components associated with regional free-air temperature and local physiographic effects.

We employ the following general model (Lundquist et al., 2008):

$$T_{(x,y,t)} = \overline{T'}_{(t)} + \tilde{T}_{(x,y,t)} + \varepsilon \tag{1}$$

where $T_{(x,\ y,\ t)}$ is the temperature (min, max, average) at a given location x, y over a time basis t; $\overline{T'}_{(t)}$ is the regional free-air temperature over time basis t within the study domain (principally capturing fluctuations associated with seasonal and synoptic

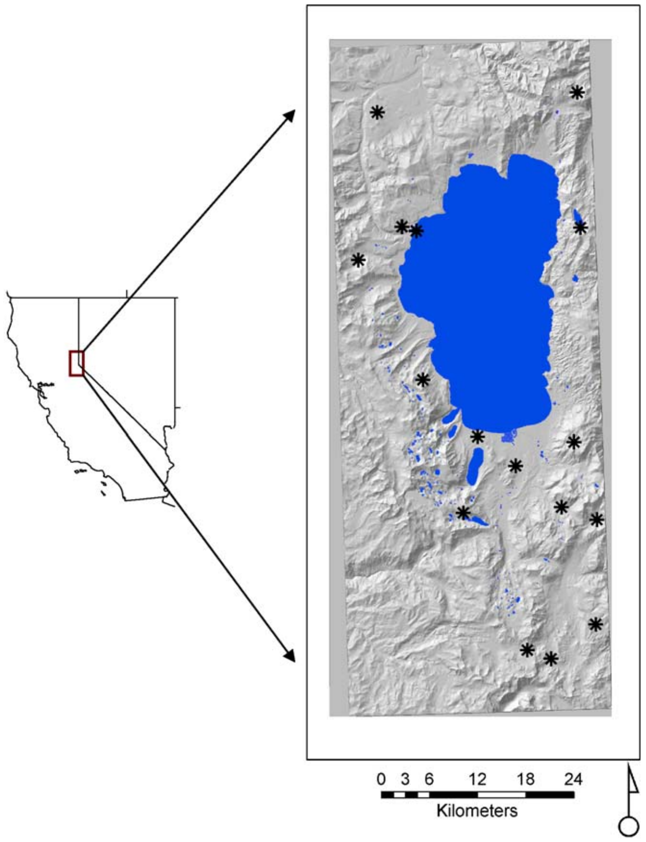

Fig. 1. Location of study site and 16 meteorological stations used in the analysis.

weather effects); $\tilde{T}_{(x,y,t)}$ are local spatial deviations driven by topoclimatic effects that vary with time, and ε is instrument and model error.

The first term in Eq. (1) accounts for temporal fluctuations in regional-scale temperatures. We characterize $\overline{T'}_{(t)}$ using free-air estimates from the North American Regional Reanalysis (NARR) dataset. NARR provides model "observations" of temperature by assimilating observations from radiosondes and satellites to provide high temporal (3 h) and coarse spatial (32 km) resolution data (Mesinger et al., 2006). As free-air temperature lapse rates may depart significantly from near-surface lapse rates within the boundary layer (Harlow et al., 2004), we consider free-air temperatures to provide an independent dataset for the analysis of surface observations. For the study area of interest, a single data point from NARR encompasses the entire domain. Daily averaged (8× daily) free-air temperatures were further interpolated to a fixed elevation of 2200 m, the median elevation of the stations.

To decompose the influence of local topoclimatic effects from regional-scale control, we first regressed daily temperature observations of average temperature (T_{avg}), minimum temperature (T_{min}), and maximum temperature (T_{max}) at all sites against the corresponding daily free-air temperature for the region (Fig. 3). The residuals of this fit represent unexplained variance in observed temperature not accounted for by the regional-scale predictor. These residuals can be attributed to the second and third terms of Eq. (1); the first of which characterizes spatial deviations from the regional mean that are a function of physiographic position on the landscape:

$$\tilde{T}_{(x,y,t)} = f(Z_{(x,y)} + I_{(x,y)} + C_{(x,y)}) \tag{2}$$

where $Z_{(x,\,y)}$ is the elevation at location x, y; $I_{(x,\,y)}$, is the mean annual daily clear sky irradiance at location x, y. This represents the effects of slope and aspect on the amount of irradiance of a surface by considering hillshading effects caused by variations in solar angle, ground slope, and aspect, as well as shadowing effects of adjacent topographic features. Clear sky irradiance (MJ m^{-2} day^{-1}) was computed at a 30 m spatial resolution and a daily time step using the r.sun algorithm (Hofierka and Suri, 2002) running under GRASS GIS 6.1 (GRASS Development Team 2005).

$C_{(x,\,y)}$ is a measure of topographic convergence and is a proxy of local convective forcings, specifically cold-air drainage at location x, y. $C_{(x,\,y)}$ is represented by the topographic convergence index (*tci*) for cell (x, y) and was calculated as $\ln(a/\tan\theta)$ where a is the upslope watershed area flowing through cell (x, y) and θ is the hillslope angle of the cell (Wolock and McCabe, 1995). *tci* values are unitless and ranged from 1 to 20 with high *tci* values representing convergent environments such as concave surfaces at the base of hillslopes and with low *tci* values representing less convergent environments such as ridge tops. We assume that cold, dense air masses will act in a manner similar to surface water and accumulate in areas with high *tci* values under stable atmospheric conditions.

We estimated the spatial anomalies described in Eq. (2) using both linear (LM) and linear mixed effects models (LME) that relate temperature residuals to the physiographic predictors described above. For LME models, a separate model was fit to daily data subset by month. Physiographic predictors were treated as fixed effects. Station ID was treated as a random effect. For LM models, a separate model was fit to data subset by month and aggregated to monthly climate normals (i.e. 16 sites by 12 months for 192 observations). For each monthly model, we examined parameter estimates and effect tests (t-test) over time. Parameter estimates and effect tests were nearly identical between the LME and LM approaches. Consequently, we opted to use the LM approach given its simplicity.

Analysis of variance (ANOVA) was used with each LM model to partition variance explained by each of the model terms and the residual error (ε; Eq. (1)). The proportion of the variance explained by each model term was calculated by dividing the sum of squares attributed to each term by the total sum of squares across all terms.

Model validation was conducted using general cross-validation. Data from a single meteorological station was withheld from the training data, LM models were fit using a step-wise model selection procedure based on the Aikaki information criterion (AIC), and selected model predictions were compared against measured temperature residuals. Root mean squared error (RMSE) was calculated. This procedure was repeated for each of the 16 stations and the average RMSE across all folds ($k = 16$) was determined. All statistical analysis was conducted using *R* (*R* Foundation for Statistical Computing).

3. Results

The 16 meteorological stations span a broad range of elevations, exposures, and landscape positions (Fig. 2). Elevation for the station sites varied from approximately 1800 to 2680 m, topographic convergence values varied from roughly 2 to 12, mean clear sky irradiance estimates varied from approximately 20–28 MJ m^{-2} day^{-1}.

3.1. Station temperature vs. free-air

The relationship between station temperature measurements and free-air estimates is summarized in Fig. 3. The percentage of the variance in measured temperature explained by free-air estimates (R^2) was 82%, 70%, and 80% for T_{avg}, T_{min}, and T_{max}, respectively. The residuals for T_{avg}, T_{min} and T_{max} appeared

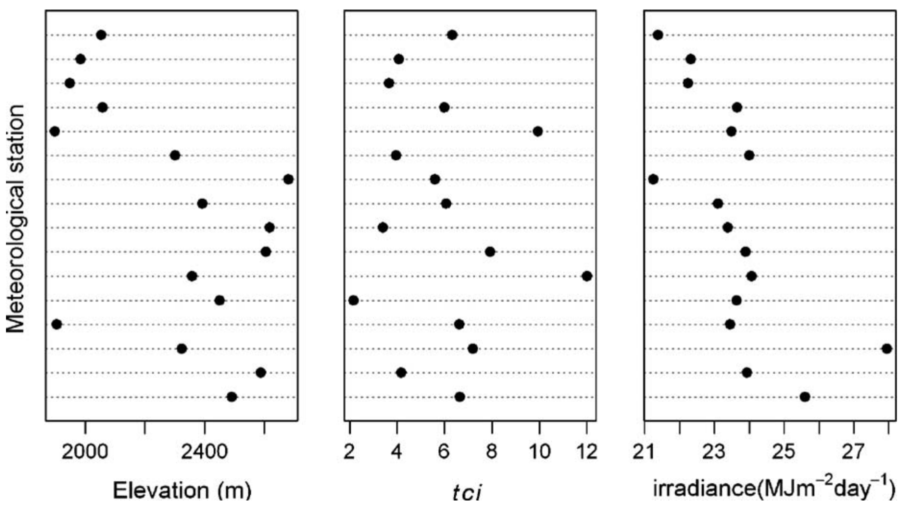

Fig. 2. Summary of physiographic variables for 16 meteorological stations found within the study area.

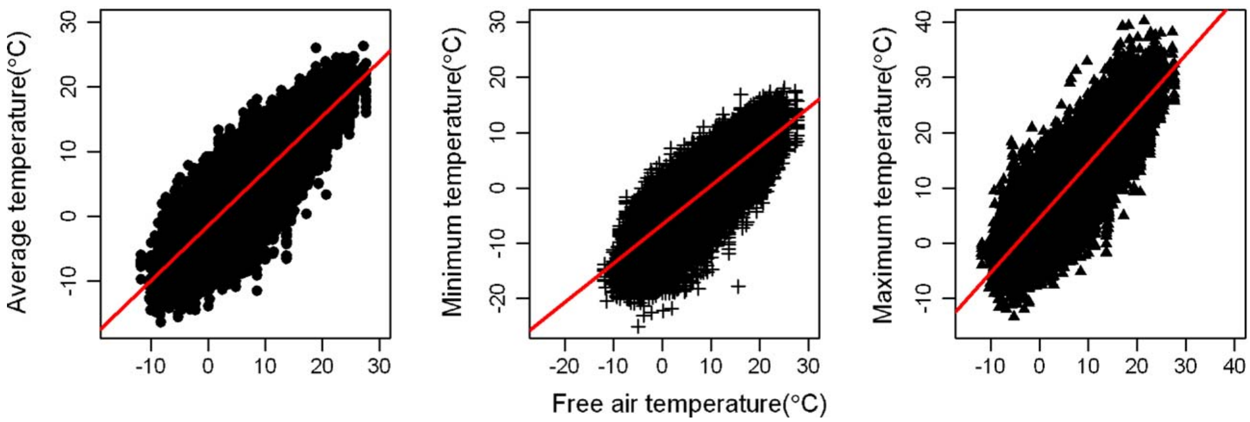

Fig. 3. Daily *in situ* temperature measurements (for average, minimum, and maximum temperatures between 1995 and 2006) by daily free-air temperature estimates over the same period. The solid line represents a simple linear regression fit. Residuals of the fits are used in subsequent analysis.

normally distributed based on examinations of normal-quantile plots.

3.2. Deviations explained by physiography

LM models relating temperature residuals to physiographic variables explained roughly 10–90% (adjusted R^2 values) of the variance in temperature residuals (Fig. 4). RMSE estimates for these models ranged from 1.2 to 2.0 °C, depending upon the type of temperature measurement and time of year (Fig. 4). For T_{avg}, the highest R^2 values and inversely, the lowest error, occurred during the spring months. Similarly, minimum temperature R^2 values were highest during the spring months and lowest during the fall. Maximum temperature R^2 values were greatest during the summer months and decreased sharply during the winter months.

T_{avg}, T_{min}, and T_{max} temperature residuals show varying temporal sensitivity to physiographic drivers. Regression coefficients for each predictor variable and associated effect test results are shown in Fig. 5. Average temperature residuals decreased with increasing elevation and topographic convergence, and increased with increasing clear sky irradiance. These results reveal that cooler conditions prevail in areas of high topographic convergence under the influence of cold-air drainage, at high elevations given a steep lapse rate, and in shaded areas in the presence of lower insolation.

While such results are consistent with expectation, we further show that the influence of these variables varies significantly over the course of the year. For instance, T_{avg} showed a greater sensitivity (larger negative values) to elevation (lapse rate) during the spring months as compared to the winter months. The mean monthly environmental lapse rate for T_{avg} was 5.3 °C km^{-1}, with the steepest lapse rates in late spring (6.5 °C km^{-1}) and the shallowest lapse rates in winter (3.9 °C km^{-1}). Additionally, the influence of topographic convergence and irradiance on T_{avg} was predominantly limited to the winter months. Elevation lapse rates for T_{min} deviations were steepest in March and April and were negligible in summer and fall. In contrast, topographic convergence had influence on T_{min} over most of the year, the effect being most pronounced in July and August. Irradiance had little influence on T_{min} deviations. Maximum temperature deviations showed sensitivity to elevation and no other physiographic variable. Lapse rates for T_{max} were steepest during the summer months and shallowest during the winter months.

3.3. Variance decomposed by model terms

We further partitioned the variance in temperature residuals by each of the physiographic predictors and error terms (Fig. 6). Elevation explained the majority of the residual variance for T_{avg} and T_{max}. In contrast, elevation explained little of the residual variance in T_{min}. *tci* was the strongest predictor for

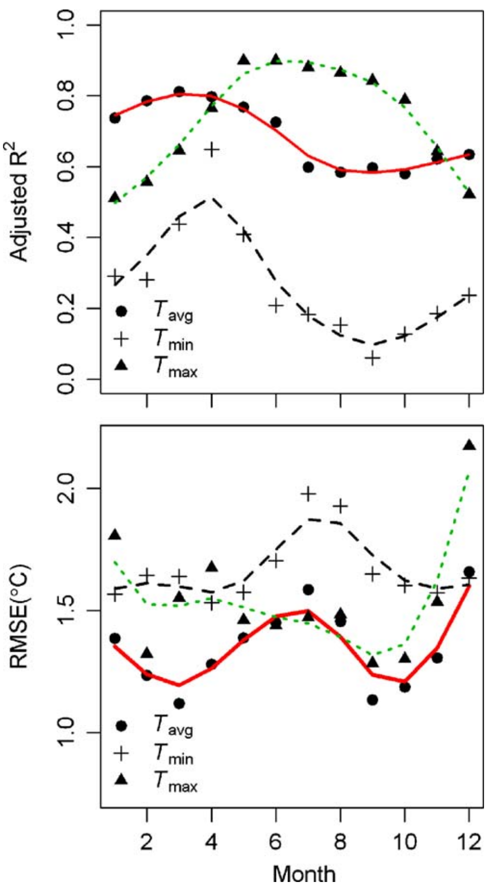

Fig. 4. Proportion of variance explained (R^2) and cross-validated estimates of root mean squared error (RMSE) for linear models relating temperature residuals to physiographic variables. Points represent values from separate models fit to monthly normals. Lines are produced using a smoothing spline (df = 6).

minimum temperature exerting influence over most of the year. *tci* also explained a moderate amount of the residual variance in average temperature, the values being the greatest in the fall and winter months. Clear sky irradiance had limited influence on the residual variance for average temperatures, the effect being limited to the winter months. The remaining unaccounted for variance was attributed to error and varied seasonally between 10–20% for T_{avg}, 40–70% for T_{min}, and 10–40% for T_{max}.

4. Discussion

4.1. Spatial and temporal variance in temperature

Temporal variability in regional conditions (i.e. free-air temperature) is the primary driver of temperatures for the stations in our study area. The combined influence of regional-scale climate and synoptic-scale weather from daily free-air temperatures explained 70–80% of the variability in *in situ* temperature measurements. Free-air temperatures alone lack the ability to describe spatio-temporal temperature patterns on both weather timescales and climate timescales (Pepin and Losleben, 2002; Pepin and Norris, 2005; Pepin and Seidel, 2005). Differences between free-air temperatures and surface observations accounted for 20–30% of the total temperature variance. These differences can principally be attributed to spatial variance in physiographic features. This finding provides an empirical basis for estimating the maximum amount of temperature variance that can be attributed to local physiography of the landscape. Given the magnitude of temporal variance in temperature due to seasonality and weather (approximately 60 °C), spatial variance of 20–30% is a substantive figure.

4.2. Elevation as a predictor of temperature

The use of elevation as a surrogate for temperature is widespread. Elevation-based lapse rates within our models differ substantially from the standard atmosphere environmental lapse rate of 6.5 °C km^{-1}, varying between being close to the dry-adiabatic lapse rate (9.8 °C km^{-1}) for summer maximum temperatures, and isothermal (0 °C km^{-1}) for minimum temperatures. Significant diurnal and seasonal differences in environmental lapse rates limit their utility in estimating temperatures (Blandford et al., 2008). Moreover, our findings demonstrate that the explanatory power of elevation varies substantially over the course of the year. For average temperature, elevation explains the majority of the spatial variability in temperature residuals during the spring months but its explanatory power drops sharply in the summer, fall, and winter months. For minimum temperatures, elevation has little explanatory power during most of the year (except the spring) due to the prevalence of temperature inversions. An analysis by the authors (Dobrowski et al., 2007) of daily environmental lapse rates for the region showed that minimum temperature lapse rates were positive in 37% of the daily observations within the study period primarily during the summer, fall and to a lesser extent, winter months. This value is consistent with other estimates of inversion frequency found in mountainous regions globally (Bolstad et al., 1998; Iijima and Shinoda, 2000).

4.3. Secondary topoclimatic effects

Secondary topoclimatic effects are prevalent during periods of the year that elevation loses its explanatory power. For example, convergent areas (high *tci* values) tend to have more negative residuals given that these landscape positions support the formation and maintenance of cold-air pools (Colette et al., 2003; Whiteman, 1982; Whiteman et al., 2004). Similar results have been demonstrated empirically by other investigators (Chung et al., 2002; Lookingbill and Urban, 2003). Our results expand on this and show that the effect of topographic convergence varies temporally becoming increasingly important during periods of enhanced atmospheric stability during the summer, fall, and winter months. These are periods of the year in which regional weather patterns in the western US promote cold-air pool formation (Lundquist and Cayan, 2007; Lundquist et al., 2008). Similarly, solar insolation has been shown to exert a positive influence on measured temperatures (Chung and Yun, 2004). Our results suggest that the radiation effect is principally relegated to the winter months. Low solar zenith angles during winter months tend to accentuate differences in solar insolation experienced on varying slope facets whereas high solar angles, terrain winds, and boundary-layer mixing during the summer months will tend to diminish sensible temperature differences. However, our meteorological station sites do not span a large gradient in irradiance values. SNOTEL stations are placed in areas that are representative of the water producing regions of a watershed as well as being accessible and protected. Consequently, sites are generally located on slopes void of strong aspect differences. This will tend to diminish strong radiation gradients between sites, thus potentially explaining why radiation had a minimal impact on the results presented.

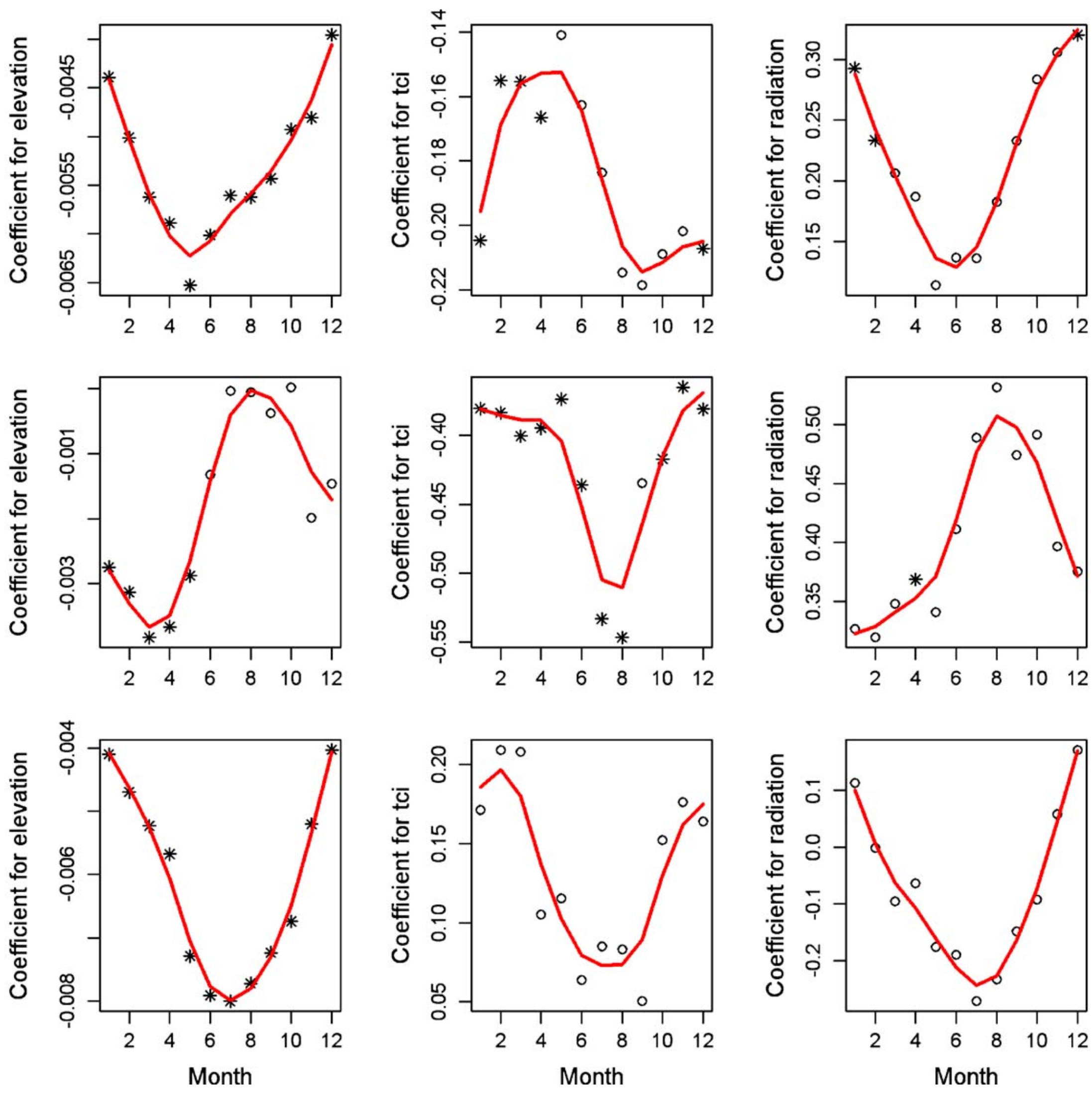

Fig. 5. Summary of regression coefficients for monthly models relating temperature residuals to physiographic variables. Results for average temperature, minimum temperature, and maximum temperature are displayed in rows 1, 2, and 3, respectively. Starred symbols denote months with significant (t-test; $p < 0.05$) effect tests. The smoothed lines are fitted using a smoothing spline (df = 6).

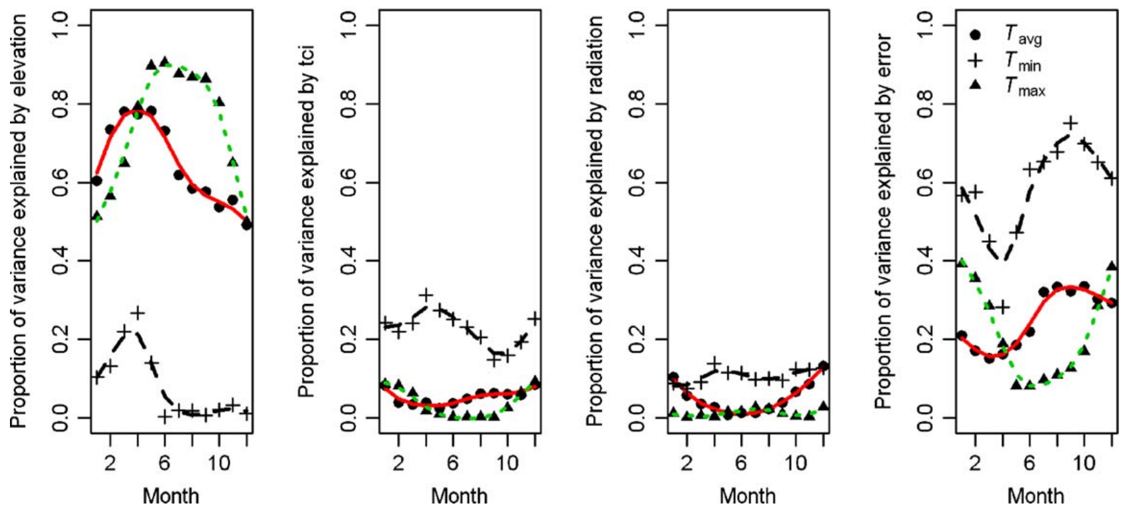

Fig. 6. Proportion of residual variance explained by each model term (including an error term). Model parameters are described in Fig. 5. Lines are produced using a smoothing spline (df = 6).

4.4. Topoclimate and spatial scale

Climate datasets used operationally often do not utilize, or do not resolve many terrain-based predictors of climate (Daly, 2006). A noted consequence of this it that there is often a disparity between the scale of many climate modeling efforts, and the biological scale at which montane organisms experience their environment. For example, modeling in climate change science using regional climate models (RCMs) and global climate models (GCMs) is conducted at scales of tens to hundreds of kilometers, while plants in mountainous regions experience their environment at a much finer scale (Urban et al., 2000). GCMs and RCMs are more likely to accurately simulate free-air temperatures than surface temperatures. The inability of these models to directly simulate features in the boundary layer (instead relying on parameterization techniques) is problematic when trying to directly use such outputs in a real world context. These discrepancies become increasingly important in the presence of terrain features, as surface temperatures are often decoupled from free-air temperatures (Grotch and MacCracken, 1991; Pepin and Seidel, 2005). Decoupling such as this is present not only on daily timescales, but also on long-term climate trend timescales (Pepin and Losleben, 2002; Pepin and Seidel, 2005; Seidel and Free, 2003).

Thus, an important issue for the development of temperature fields is determining the spatial scale at which physiography mediates regional temperature. This is analogous to assessing the scale at which physiography varies in mountain environments. To our knowledge, there has been surprisingly little research in this area. An exception to this is provided by Urban et al. (2000) who characterized the spatial grain of elevation, transformed aspect (a measure of solar insolation), and topographic convergence (*tci*) over three spatial extents in the Sierra Nevada using variogram analysis. They showed that at the largest spatial extent (90,000 ha), elevation showed no obvious grain, transformed aspect varied on the scales of 800–1000 m, while *tci* varied at roughly 200 m in scale. When examined at smaller spatial extents, both aspect and *tci* showed even finer spatial grain. These findings coupled with our results and previous landscape-scale research on air temperature in mountain environments (Chung et al., 2002; Chung and Yun, 2004; Lookingbill and Urban, 2003) suggest that significant variation in temperature is occurring at scales of less than 1 km. In particular, minimum temperature, with its strong sensitivity to cold-air drainage, is likely to vary at scales less than 200 m.

4.5. Practical implications

Our findings have practical implications for the use of temperature data in landscape-scale research efforts. First, our approach is functionally a means to statistically downscale outputs of regional climate estimates to local scales. GCM or RCM outputs could be used instead of the NARR data within our modeling framework, thus allowing for forecasting capabilities under climate change scenarios. Combining GCM/RCM outputs and topographic data in this fashion will lead to improved datasets in climate change impact studies.

Second, the magnitude and timing of topoclimatic effects is contingent upon regional-scale circulation patterns. For instance, periods of mixed atmospheric conditions lend themselves to the use of simple elevation-based lapse rate models. Model fit for average temperature was highest during the spring months and was principally driven by elevation as a predictor. This suggests that for our study area, simple lapse rate estimates of temperature are best applied during the spring, a useful finding given the strong influence of spring temperatures on hydrologic and phenologic processes [e.g. snow melt, bud burst, frost tolerance—(Cayan et al., 2001; Gutschick and BassirRad, 2003; Inouye, 2000; Saxe et al., 2001; Stewart et al., 2004)]. Conversely, secondary topoclimatic effects (e.g. cold-air drainage) become more prominent during periods of enhanced atmospheric stability (Whiteman, 1982; Whiteman et al., 2004). For example, the sensitivity of minimum temperature to *tci* was greatest during the summer and fall months, periods with clear and dry conditions often associated with high pressure systems. Consistent results were shown by Lundquist et al. (2008) in the Sierras and (Blandford et al., 2008) in the northern Rockies. Relating projected changes in regional circulation patterns through their influence on fine-scale physiographic factors may provide an additional means to estimate temperature changes at scales relevant for ecological assessment.

4.6. Ecological implications

Temperature fields are used widely in ecological research and are particularly critical to climate change impact assessments. Although temperature is commonly used to predict the distribution of species, temperature is not likely to directly constrain montane species distributions except at the highest elevations (Koerner, 1998). Instead, temperature principally affects water balance which has a dramatic influence on species distributions (Stephenson, 1998), particularly in the arid western US.

Topoclimatic effects have an unambiguous influence on temperature and thus water balance. To demonstrate this, we calculated reference evapotranspiration for two hypothetical sites [E_{to}, Thornthwaite method (Thornthwaite, 1953)] using monthly average temperatures predicted from our monthly models. The first 'warm' site has high solar irradiance and low topographic convergence ($tci = 2$, $I = 30$ MJ m^{-2} day^{-1}—values that fall well within the range of those modeled within our study area). The second 'cool' site has low solar irradiance and high convergence ($tci = 15$, $I = 20$ MJ m^{-2} day^{-1}). Both sites are modeled at 2000 m in elevation; thus, the difference in annual temperature profiles between these sites is solely driven by landscape position independent of elevation. The absolute difference in mean monthly temperatures between these 'sites' range from 0 °C in the spring to approximately 5 °C in the winter months (results not shown). These differences may seem inconsequential; however, the annual integration of these differences has a pronounced effect on water

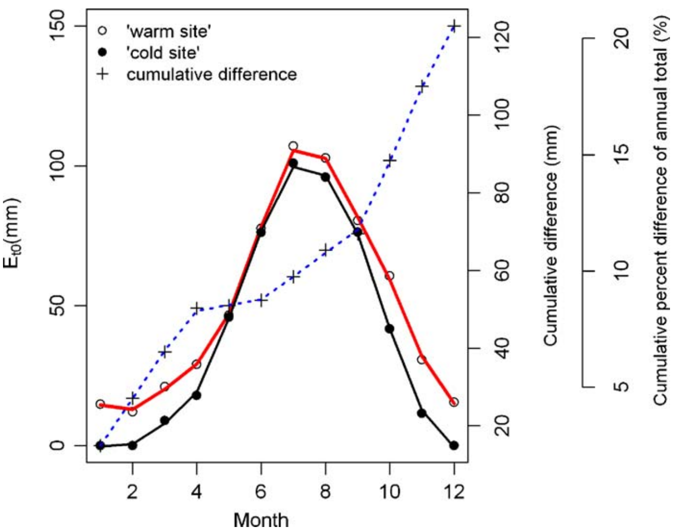

Fig. 7. Reference evapotranspiration (E_{to}) for two hypothetical sites calculated using the Thornthwaite method. Sites share the same elevation but vary in topographic convergence and solar insolation (see discussion for further detail). Temperatures used in the E_{to} calculation were predicted using monthly models for average temperature. Cumulative percent difference normalizes cumulative difference in terms of the mean annual E_{to} for the two sites (537 mm).

balance. Our hypothetical sites vary in E_{to} by approximately 120 mm, a value that is over 22% of the mean annual total of the sites (Fig. 7). It should be noted that this estimate is likely to be conservative. The Thornthwaite method of E_{to} calculation only utilizes monthly average temperatures. Evapotranspiration is also influenced by solar insolation, wind speed, and other variables that will further emphasize differences between sites. Simply stated, subtle differences in temperature associated with landscape position, can result in large differences in water balance, which are manifest in a host of hydrologic and ecologic processes.

4.7. Conclusions

The results we presented in this study are applicable to the narrow range of physiographic and climatic conditions found in the study area. With any empirically based statistical model, caution should be used when trying to extrapolate findings beyond the domain of the analysis. Despite this, our results put some initial bounds on describing the spatial and temporal influence of landscape-scale physiography on temperature patterns. Further, they highlight the ability of simple terrain analysis techniques to improve temperature estimates in areas of complex terrain.

In summary, we demonstrate that for our study area: (1) regional temperature patterns are the principle driver of local temperatures. (2) After removing the effect of regional temporal patterns, the remaining variance (20–30%) can be largely explained by spatial variability in landscape-scale physiography. Variables derived from terrain modeling techniques can be used to describe this spatial variability and link regional free-air temperatures to *in situ* measurements. (3) The influence of physiographic drivers varies temporally and is influenced by regional conditions. Periods of well-mixed atmospheric conditions lend themselves to the use of simple lapse rate models for temperature estimation. Conversely, secondary topoclimatic effects become most prominent during periods of enhanced atmospheric stability. This is particularly relevant when modeling minimum temperatures in areas of complex terrain. (4) Lastly, cumulative differences in temperature due to landscape position can have a prominent effect on water balance, and as a result, hydrologic and ecologic processes.

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